SOIL WARMING AND DRYING AND THE CONSQUENCE TO CROP YIELDS AMONG CONSERVATION TILLAGE PRACTICES IN FRIGID CORN-SOYBEAN FIELDS

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Program:
Environmental and Conservation Sciences

June 2017

Fargo, North Dakota

North Dakota State University
Graduate School

Title

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MASTER OF SCIENCE

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ABSTRACT

Concerns over delayed soil warming and drying have hindered adoption of conservation tillage practices in frigid environments. Our objectives were to evaluate the effects of chisel plow (CP), vertical tillage (VT), strip tillage with coulters (STC), and strip tillage with shanks (STS) on soil warming and drying and their potential consequences to crop yields. A two-year study was conduct at three full-scale, producer-managed, corn-soybean fields in the Red River Valley of eastern North Dakota and western Minnesota. Tillage treatments were assessed to measure crop residue cover, soil temperatures, soil volumetric water contents, crop yields, and other metrics. Our study indicated significant differences for many soil physical and chemical parameters, but little to none for soil warming and crop yields. Yield differences were attributed to varying fertilizer management practices, timing, and application method. These findings emphasize the importance of field management practices that compliment conservation tillage for obtaining competitive crop yields.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Aaron Daigh, for providing the opportunity for me to work on this research and constantly pushing me to reach my full capability. I would also like to thank Dr. Larry Cihacek and Dr. Kenneth Lepper for being on my graduate committee. I also appreciate the support and knowledge that I have gained from Jodi DeJong-Hughes, at the University of Minnesota Extension, and Dr. Abbey Wick during my research in the field. I would also like to thank Radu Carcoana for his assistance in the field and his dependability. I appreciate Mike, Charlie, and Ken for your support, patience, and willingness to allow this research to take place and continue to be ongoing. Lastly, thanks to the North Dakota Soybean Council, North Dakota Corn Council, Minnesota Soybean Growers, Minnesota Corn Research and promotion Council, and the North Dakota Agricultural Experiment Station for helping to fund this research.

DEDICATION

To whom I care, to whom I love,

The dignity is high, bravery is shy

To whom I admire, to whom I sincere

The sky is blue, whenever we do

To my parents and wife, to my uncle I survive

Happiness is wide, and enjoy the ride

To my hero may I thrive

The smile is dive, the smile is dive

Saddam Hussain, Mastour Ali Alghamdi, Saeed and Fawzia Alghamdi, Abdullah Safar Alghamdi, and Megan Ehora.

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GENERAL INTRODUCTION

Research on tillage and crop production has taken place for over a century (Sewell, 1919). The U.S. Dust Bowl of the early 20th century ignited greater conversation and interest among stakeholders to examine the effects of agricultural management practices, such as tillage, on not only crop yields, but also the indirect effects on the environment and long-term agricultural sustainability (Worster, 2004). Since that time, the evaluation of best management practices for sustainable agriculture has been in the forefront of research at Land Grant universities. Conservation tillage (i.e., reduced tillage), its definition, practice and understanding, has also progressed. The scientific literature included in this thesis provides evidence supporting the ideas that reducing tillage practices provide long-term benefits to crop production and the environment.

The Upper Great Plains region is a primary producer of agricultural products in the U.S. However, in the Red River Valley (RRV) of the north (i.e., eastern North Dakota and western Minnesota), short growing seasons and extreme temperatures are just two of the challenges crop producers face (Rosenberg, 1987). Currently, soil and residue management practices, such as tillage, vary widely among producers (i.e., moldboard plowing to no tillage). The overuse of tillage can set in place a series of soil degradation processes such as erosion and nutrient loss (Lal, 1991). A substantial percentage of the RRV and surrounding lands are under conventional tillage or no-till, while a smaller percent is managed with other reduced tillage practices (USDA, 2016a). Generally, the adoption of conservation tillage practices is hindered by producers' concerns with adequate soil warming and drying during the spring months in the region's frigid soils (Pedersen and Lauer, 2003). Although many conventional-tillage producers are interested in practices to conserve their soil and promote soil health, the concerns with soil warming and drying is envisioned as an added risk for converting their lands directly to no-till practices; even though many examples of successful no-till farms are present throughout North Dakota and Minnesota. However, these producers may perceive alternative reduced tillage practices (e.g., vertical tillage, strip tillage, and chisel plowing) as having lower associated risk than no-till practices. Therefore, research and demonstration of such reduced tillage practices in the region are needed to help bridge the gap for producers interested in reducing tillage operations but who are also hesitant to convert to no-till due to the perceived risks of lower crop yields.

In the frigid soils of the RRV, it is hypothesized that there are significant differences among conservation tillage treatments in regards to soil warming and soil drying, but these effects often do not translate into differences in crop yields. Instead, crop yield differences are expected to be functions of whether soil nutrients were adequately delivered to the crop or soil physical degradation (e.g., smearing, erosion, etc.) during tillage. Additionally, there is no peer-reviewed published research from North Dakota and western Minnesota on conservation tillage implements effects across a wide range of soil textures accompanied by detailed measurements of soil physical conditions and chemical properties, along with crop yields using full-sized equipment on producer's fields. The North Dakota climate is subject to short growing seasons; therefore, an understanding on the relationship between soil warming and soil texture may aid North Dakota farmers in making best management decisions. Our objectives were to evaluate the effects of chisel plow (CP), vertical tillage (VT), strip tillage with coulters (STC), and strip tillage with shanks (STS) implements on soil physical conditions (i.e., soil warming and drying) and properties and their potential consequences to crop yields. A two-year study was conducted at three full-scale, producer-managed, corn-soybean fields in the Red River Valley of eastern North Dakota and western Minnesota where tillage treatments were assessed to measure crop residue cover, soil temperatures and soil volumetric water contents using techniques to account for spatial and temporal representativeness, crop yields, and a variety of other metrics (i.e., soil chemical properties, penetration resistance, plant heights and populations) that could potentially account for crop yield differences.

LITERATURE REVIEW

Cropland Tillage

In general, tillage aids in preparing the soil for an ideal environment where plants can thrive according to the needs of the producer (Klute, 1982). In soils that are compacted, plants may face a difficult time penetrating the soil for growth. Therefore, loosening the soil helps farmers grow plants that can germinate and thrive (Kargas et al., 2012; Soane and van Ouwerkerk, 1994; Kaspar et al., 1990; Schneider and Gupta, 1985; Gustafson, 1941). However, one of the principle challenges with tillage is the potential for wind and water erosion. Water erosion is a global problem and is common with high rainfall events and surface runoff. Erosion alters the soils chemical, physical, and biological properties (Pimental et al., 1995; Lal, 2001). These alterations can lead to crop production losses in an agricultural setting and are therefore costly. In the U.S., estimates of the annuals costs of soil erosion have ranged from 100 million (Crosson, 2007) to 44 billion USD (Pimental et al., 1995). For this reason, variations in traditional cropland tillage (i.e., the mechanical incorporation of surface crop residues by the inversion or turning up of soils) have evolved to reduce wind and water erosion and soil degradation (Baker and Laflen, 1983).

Acts and Interventions to Conserve U.S. Croplands

Since the early 18th century, colonists migrating from Europe to the modern day United States (U.S.) depended on the use of crop residue (organic matter) to reduce soil erosion (Moldenhauer et al., 1994). During the 19th century, farmers mostly relied on their own informal experimentation (i.e., trial and error) and rooted traditions to investigate new farm management practices (Iles and Marsh, 2012). By the mid-1800s, research conducted via statewide agricultural experiment stations was exploring soil tillage and the effects on erosion and organic matter (Lee, 1849; Waters, 1888). Through the Hatch Act of 1887 and the Smith-Lever Act of 1914, research stations through the Land Grant universities were established and then expanded to begin investigating alternative tillage practices. In North Dakota, there was still a primary focus on determining appropriate tillage practices to ensure premium yields (Shepperd and Jeffrey, 1897). In 1890, the North Dakota Agricultural Experiment Station was established in Fargo, ND. To date, the state of North Dakota operates seven research extension centers. In the 1920s, research priorities to investigate the primary causes of soil erosion in agricultural fields gained popularity (Bennett and Chapline, 1934). However, research studies were sparse and with a scope of only regional or local influence.

The U.S. Dust Bowl of the 1930s is one of the greatest environmental catastrophes in American history. The environmental conditions caused by the Dust Bowl resulted in large economic losses for landowners and rural residents, forcing the displacement of over two million people on the Great Plains (Interstate Migration, 1941; Hoyt, 1936). The environmental effects of the Dust Bowl included severe soil degradation and erosion, leading to a decline of crop production (Worster, 2004). However, the severity of these environmental effects prompted numerous changes, including the investigation of tillage practices, to conserve soil resources in the United States.

The Conservation Technical Assistance program was established and designed to plan and install best management practices to reduce the environmental effects of soil erosion (Rasmussen et al., 1976). After World War II, the U.S. Department of Agriculture (USDA) in collaboration with scientists at Land Grant universities determined that soil erosion could be effectively mitigated with best management practices for tillage operations (McCalla and Army, 1961). At that time, tillage operations that promoted greater roughness of the soil surface (crop residue) was one management practice for controlling wind and water erosion (Van Doren and Stauffer, 1943). Best practices included secondary cultivation to control the spread of weeds (Hoeft et al., 2000b; Allmaras and Dowdy, 1985; Gustafson, 1941). In the 1950s, farmers began transitioning away from the use of the moldboard plow to the use of the chisel plow (Lal et al., 2007). By the 1960s and 1970s, other conservation tillage practices began to emerge, including ridge tillage and strip tillage, defined by the Conservation Technology Information Center (CTIC) as "reduced tillage" practices (Mitchell, 2009). Reduced tillage was defined by CTIC as tillage that maintain 15-30% of crop residue on the soil surface (Mitchell, 2009). Although still ambiguous in definition, the Soil Conservation Service (SCS) of the USDA began recording the number of planted acres under conservation tillage in 1963 (Schertz, 1988; Allmaras and Dowdy, 1985).

In the 1970s and into the 1980s, the agriculture demand coupled with increased agricultural output prices, hindered the adoption and interest of conservation tillage for many farmers (Worster, 2004). Research in the Upper Great Plains region determined that this region was the second most prone to losses for nutrients, only behind the Corn Belt region (Larson et al., 1983). In 1984, the SCS continued to refine the definition of conservation tillage as any tillage operation that reduces water erosion and maintain 30% crop residue on the soil surface or 1,000 kg/ha of crop residue (MWPS, 2000). The 1985 Farm Act was also instrumental in defining highly erodible land, residue cover requirements, providing a focus on conservation tillage, and establishing the Conservation Resource Program (CRP) (Rasnake et al., 1986).

Lal (1990) defined conservation tillage as a method of seedbed preparation that encouraged soil surface roughness and the conservation of crop residue mulch on the soil surface. In 1992, the Upper Great Plains region ranked as the third most prone to wind erosion and second in water erosion (USDA, 1995). In 1996, the Federal Agriculture Improvement and Reform (FAIR) Act of 1996 was enacted to modify conservation compliance requirements put in place by the Food Security Act of 1985 (Uri, 1999). Modifications provided great flexibility in all areas of the act; however, with greater flexibility became greater responsibility. Farmers not in compliance with the act were held to severe penalties and/or loss of benefits. Until recently, it was difficult to accurately track the percentage of cropland under conservation tillage, due to inconsistent definitions of the practice. Plant residue present from the previous crop at the time of planting is the modern practical field measurement used to categorize a tillage practice. The lower limit of conservation tillage can be defined as tillage leaving behind at least 30% of the crop residue on the soil surface (Tiessen et al., 2010; CTIC, 2004). Conventional tillage can be categorized as any tillage practice leaving behind less than 30% of crop residue on the soil surface. Conservation tillage is a broad term used to define no-tillage, minimum tillage, and/or ridge tillage (Baker et al., 2006). According to the most recent Census of Agriculture, approximately 62% of U.S. cropland is managed using conservation tillage practices (USDA, 2016b). Currently, 36.4% of North Dakota agricultural lands are under conventional tillage management practices, representing 3.2 million hectares of land (USDA, 2016a). No-till management practices are being implemented on 35.7% of cropland (3.1 million hectares), while 27.9% (2.5 million hectares) are under conservation tillage (reduced tillage) management practices.

Cropland Environment in the Upper Great Plains of North Dakota

The long winters in the frigid Upper Great Plains region of the United States result in short growing seasons for corn-soybean systems. The geographical area of the Upper Great Plains extends between the states of Iowa, Minnesota, Montana, Nebraska, North Dakota, and

South Dakota. The thermal environment range is generally cold in the Red River Valley (RRV) of the north (i.e., eastern North Dakota and western Minnesota) with 15-year means for the annual minimum, maximum and average temperatures of 0°C, 11°C, and 6°C, respectively, in Wahpeton, ND (NDAWN, 2017). North Dakota currently holds the third largest variation of highest and lowest temperatures of all U.S. states and has the largest variation in temperatures among all non-mountainous states (NOAA, 2017a).

Approximately 50 and 75% of all agricultural farmlands in northern and eastern ND are actively growing row crops; whereas, in southwestern ND, less than 15% of farmlands are made up of row crops (Carter, 1994). In this region, annual precipitation and the number of frost-free days are among the greatest concerns for producers in the region (Carter, 1994). The number of frost-free days annually, based on a 30-year mean (1981-2010), is between 120-130 days in both North Dakota and Minnesota (NOAA, 2017b; Carter, 1994).

Implementing conservation tillage, such as NT and reduced tillage, is increasing in popularity in the Upper Great Plains of the U.S., although there are still many producers who have an interest in using the more aggressive conventional methods to dry and warm poorly drained soils of the RRV (Alletto et al., 2011; Licht and Al-Kaisi, 2005; Drury et al., 1999). Soils with higher levels of crop residue cover may delay plant growth and therefore crop yields (Griffith et al., 1973; Mock and Erbach, 1977; Dick and Van Doren, 1985). However, research conducted by Christov et al., (1982) concluded that poorly drained soils may not respond to conservation tillage practices in the same ways as in well-drained soils.

Conservation Tillage Implements of Interest

Conservation tillage implements that are frequently noted and are of interest in this thesis include chisel plow (CP), vertical tillage (VT), strip tillage with coulters (STC), and strip tillage with shanks (STS). In general, less intensity of soil disturbance via tillage results in less wind and water erosion (Reicosky, 2015; Soil Science Glossary Terms Committee, 2008). No-till (NT) leaves most soil undisturbed, while providing protection from erosion (Reicosky, 2015). Strip tillage provides an opportunity to reduce tillage by limiting the total surface area tilled, thereby leaving surface crop residue in place (Baker et al., 2006; Campbell et al., 1996). Some research classifies ST as a moderate intermediary to both conventional and conservation tillage practices, leaving a limited amount of soil residue and a portion of undisturbed soil in between narrow tillage rows (Baker et al., 2006). In general, STC and STS vary based on the tool used within the row during tillage. The purpose of vertical tillage is to cut through, size, and mix crop residue, resulting in varying crop residues amounts on the soil surface (Nowatzki, 2013; Klingberg and Weisenbeck, 2011). Vertical tillage adoption has significantly increased in North Dakota over the last five years (Nowatzki, 2013) and this practice can include the use of various types of implements. Tillage using a chisel plow is the least conservative of these practices since it incorporates most of the crop residue into the soil while using more intense tillage components including varying sweeps, spikes, and shovels with various options of twists and angles (Reicosky, 2015). The choice of a tillage practice a producer may implement varies upon multiple factors. Soil texture, soil depth, crop, climate, and socioeconomic resources are among the varying reasons of selecting a suitable conservation tillage practice (Gajri et al., 2002).

Crop Growth and Yields under Conservation Tillage Practices

Buman et al. (2004) examined variations in crop production and soil properties in corn-soybean fields under ST, NT, and conventional tillage. When observing crop emergence, no significant differences were noted among varying tillage practices. Similar results were documented by Vetsch and Randall (2002) in Minnesota where emergence in continuous corn-

corn fields was slightly different among CP, NT, ST, and zone tillage (ZT). The crops under CP in corn-corn fields emerged faster as compared with ST and ZT practices, but were not significantly different ($p \leq 0.10$) since they observed ≤ 1 day difference in emergence. Yield variances were less than 3% among all treatments in the continuous corn-corn fields. No significant differences in yields were observed in rotated corn-soybean fields. Some studies have indicated increased crop yields under NT, when compared to conventional practices (Pedersen and Lauer, 2003; Hussain et al., 1999; Norwood, 1999; Dickey et al., 1994; Ismael et al., 1994). Others have noted decreases in crop yields under NT practices, though not always statistically significant (Salem et al., 2015; Pedersen and Lauer, 2003; Hoeft et al., 2000a; Vyn and Raimbault, 1992). Daigh et al. (2017) investigated crop yield effects of long-term (8-51 years) rotated corn-soybean fields and continuous corn-corn fields under NT and CP tillage practices at eight field sites across the Midwestern US corn-belt. For continuous corn and the corn phase of corn-soybean rotation, they concluded slight differences in yield for the varying practices (favoring CP), but noted some benefits to NT during periods of drought. During the soybean phase of the corn-soybean rotation, no significant differences in yield were observed for any site-year.

Conservation tillage in the Upper Great Plains is sensitive to climatic conditions, soil properties, cropping systems, and needs of conserving soil water while reducing wind and water erosion (Carter, 1994). Pedersen and Lauer (2003) and Vetsch and Randall (2002) examined crop yields under NT in Wisconsin and Minnesota and concluded that in a northern temperature climate, cropland under NT can demonstrate a reduced yield due to reduced soil temperature and subsequent delayed crop emergence. In an area subject to extreme temperatures, short growing seasons, and varying soil textures, a detailed assessment of soil warming and crop yield interactions is essential for developing recommendations for producers interested in building soil health via reducing their tillage practices.

Soil Warming under Varying Tillage Practices and Gaps in the Scientific Literature

Research examining conservation tillage practices effects on soil warming and crop responses is noted in the below and above text, respectively. However, many of these studies were concentrated in areas (e.g., Iowa, Nebraska, Illinois, Indiana, Ohio) that are substantially different climatically and in parent material than in the RRV of eastern North Dakota and western Minnesota. For example, the growing seasons in Iowa and Nebraska are around 160 days (Lincoln Weather and Climate, 2017; NOAA, 2001), whereas the growing season of the RRV is between 120-130 days.

On average, conventional tillage systems reported in the literature have shown soil temperatures to be higher than NT systems (Gauer et al, 1982; Mock and Erbach, 1977; Lal, 1974). Soil warming is known to be slower in reduced tillage practices due to residue coverage that reflects solar radiation and undisturbed soil having a higher thermal conductivity to spread out heat deeper into the soil profile (Johnson and Lowery, 1985; Mock and Erbach, 1977; Moody et al., 1963; Burrows and Larson, 1962; van Wijk et al., 1959). Moody et al. (1963) determined that mulching slowed the soil warming; however, was beneficial for crop growth and yield when compared with bare soils. This was concluded to be a result of increased volumetric water content holding capacity of higher residue cover and decreased evaporation at the soil surface, as other studies have also confirmed (Kargas et al., 2012; Su et al., 2007). Other studies indicate that decreased soil temperature is likely due to higher volumetric heat capacity from higher organic matter content's ability to absorb and retain more soil water (Busari et al., 2015; Lozano-Garcia and Parras-Alcantara, 2014).

Griffith et al. (1973) examined ST operations versus conventional tillage practices and determined that in-row soil temperatures were higher for ST as compared with NT practices, but cooler than conventional practices. A study by Rasmussen (1999) examined soil temperature and evaporation in fields under conservation tillage in the Scandinavian countries of Denmark, Finland, Norway and Sweden. Results indicated a reduced evaporation rate, linked to a lower soil temperature of land under conservation tillage. Other studies have also demonstrated the interrelated relationship of soil volumetric water content and soil temperature (Radke, 1982; Morrison and Gerik, 1983; Griffith et al., 1973). Radke (1982) concluded that wet soil has a greater heat capacity than dry soil and that energy inputs to the soil surface may often be partitioned more into the latent heat of evaporation, rather than storage for the warming the soil. General findings have indicated that ST is effective in conserving soil volumetric water content and contributes to improved plant emergence when compared with NT (McVay et al., 2006; Pagliai et al., 2004).

Sims et al. (1998) examined the effects of the thermal environment on tillage management and corn crop yield. In their research, adoption of NT practice and succeeding yields varied from eastern Nebraska to southern Nebraska. Soils at field sites were Mollisols with argillic horizons, but varying soil surface textures of silt loam and silty clay loam. Sims et al. (1998) concluded that NT management practice could be viable in a drier climate with silt loam soils, indicating that thermal environment and soil texture play a role in dictating appropriate tillage management practices best suited for the landscape. Another study by Licht and Al-Kaisi (2005) investigated NT and alternative conservation tillage practices and their effects on soil physical properties in Iowa. Results indicated that STS could provide similar benefits of soil warming (in the early spring) to that of the CP, though not significantly different from NT, and conserved soil volumetric water content comparative to NT. They noted that there was a relationship between soil warming and the air temperature for STS and CP practices, where soil warming occurred directly with air temperature warming. Under STS, peak soil warming occurred as air temperature reaches its daily maximum (mid-day). They suggested that in a frigid environment soil warming under STS and CP practices may not be as evident in frigid soils. Conclusions indicated that implementation of reduced tillage systems would be highly dependent on site-specific field conditions, similar to other short-term studies that concluded that variations in soil texture could contribute to differences observed among varying tillage practices (Hussain et al., 1999; Ismael et al., 1994).

Salem et al. (2015) examined the short-term effects of conventional tillage (moldboard plow), minimum tillage (CP), reservoir tillage (CP followed by mini-depressions/holes created with hand push tool), and zero tillage on cornfields in Spain. Soil volumetric water content and soil temperature was near continuously monitored at 20 and 40 cm and at 5 and 12 cm, respectively. Results of their study indicated that there were no significant differences in soil volumetric water content for all tillage practices at both depths in the growing season and at harvest. Differences in soil temperature were observed among various tillage implements; however, data analysis only included 12 days of soil temperature continuous readings in May, June, and July, resulting in only 36 days of unique temperature readings. Despite the study being short-term in scope, conclusions based on a small number of readings may not be a best practice to consider in North Dakota and western Minnesota, especially with the extreme temperatures of the region. Using near continuous data readings throughout the entire growing season would result in a more accurate account of tillage implement effects on soil temperature. Other limitations of their study included the restriction to a small-plot design (25 m x 4.5 m), and therefore, the absence of full sized tillage implements in the study. A large portion of the tillage literature report on studies with similar limitations in regards to plot size and measurement frequencies to when evaluating soil warming and drying with subsequent consequences to crop yields. In the frigid soils of the RRV and surrounding region, there is no peer-reviewed published research on conservation tillage implements effects across a wide range of soil textures accompanied by detailed measurements of soil physical conditions and chemical properties, along with crop yields using full-sized equipment on producer's fields.

A substantial percentage of the RRV and surrounding lands are under conventional tillage or NT, while a smaller percent is managed with other reduced tillage practices (USDA, 2016a). Generally, the adoption of conservation tillage practices is hindered by producers' concerns with adequate soil warming and drying during the spring months in the region's frigid soils (Pedersen and Lauer, 2003). Although many conventional-tillage producers are interested in practices to conserve their soil and promote soil health, the concerns with soil warming and drying is envisioned as an added risk for converting their lands directly to NT practices; even though many anecdotal examples of successful NT farms are present throughout North Dakota and Minnesota. However, these producers may perceive alternative reduced tillage practices (e.g., vertical tillage, strip tillage, and chisel plowing) as having lower associated risk than NT practices. Therefore, research and demonstration of such reduced tillage practices in the region are needed to help bridge the gap for producers interested in reducing tillage operations but who are also hesitant to convert to NT due to the perceived risks of lower crop yields.

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SOIL WARMING AND DRYING AND THE CONSEQUENCE TO CROP YIELDS AMONG CONSERVATION TILLAGE PRACTICES IN FRIGID CORN-SOYBEAN FIELDS

Abstract

The long winters in the frigid Upper Great Plains region of the United States result in short growing seasons for corn-soybean systems. Historically, producers implement aggressive tillage practices to warm the soil in the spring months. Although, producers show a growing interest in building soil health, many of these producers are hesitant to adopt reduced tillage practices due to assumptions about the consequences to crop yields. Therefore, our objectives were to evaluate the effects of soil warming and drying, soil quality parameters, and crop performance as a result of select reduced tillage practices including vertical till (VT), strip till with shanks (STS), strip till with coulters (STC), and chisel plow (CP). Large tillage plots (12 x 550m per plot) were installed at three producer farms in the Red River Valley of eastern North Dakota and western Minnesota using randomized complete block designs with three replicates at each farm. Five soil series among the farms ranged from sandy loams to silty clays and had a variety of surface drainage ditches, subsurface drains, and soil salinity levels. Crop residue cover, soil temperature (T), volumetric soil water contents (θ), soil thermal properties, soil penetration resistance, soil chemical properties, plant populations and heights, and crop yields were measured in 2015 and 2016. Soil T and θ was monitored biweekly near the soil surface (0 - 12cm depths) using handheld sensors for spatial representativeness and near-continuously with deployed monitoring stations at 5, 10, 25, and 40 cm depths for temporal representativeness. Results showed little to no significant differences in soil warming and drying among CP, STC, STS, and VT reduced tillage treatments. When differences were detected, STC and STS in the

tilled zone was similar to CP and significantly different from VT, STC, and STS in the untilled zones for the soil temperatures, volumetric water content, soil penetration resistances. The benefit of ST treatments was demonstrated by soil warming and drying during the early growing season in the tilled zones, whereas higher volumetric water content where found in the untouched zones during the mid-growing season. Crop yields were inconsistent with soil temperatures and volumetric water content; instead, fertilizer applications and methods were notably related to crop yields.

Introduction

The Red River Valley (RRV) of the North is situated in eastern North Dakota and western Minnesota where approximately 81% of the land use is agricultural and 66% is in row crop production due to the fertile soils of the region (Ag Statistics, 2008; Christensen, 2007; Leistritz et al., 2002; Stoner et al., 1998). Conservation tillage efforts, such as no-till (NT) and reduced tillage, have increased in popularity in the region. As of 2012, producers implemented conservation tillage practices on 63.6% of the cropland in North Dakota (i.e., 5.7 million hectares) (USDA, 2016a). However, many producers of the remaining 36.4% of croplands in the region still use more aggressive soil tillage practices to aid soil warming and drying during the cold spring months due to the short (120-130 days annually) frost-free growing season (NOAA, 2017a; USDA, 2016a). These producers have therefore been hesitant to try alternative reduced tillage practices, such as strip tillage (ST) and vertical tillage (VT), due to assumptions that these practices do not warm and dry the soil as effectively as chisel plowing (CP), even though a large portion of these producers are interested in building soil health (Vetsch and Randall, 2002). These producers infer that slower soil warming can lead to delayed seedling germination and growth (Davies et al., 1993) and thus reduce crop yields (Buman et al., 2004). Although Vetsch and Randall (2002) indicated no significant difference in crop emergence in continuous corn-corn and rotated corn-soybean fields in southern Minnesota under reduced tillage practices, detailed on-farm studies of soil warming and drying with subsequent consequences to crop yields in the frigid RRV soils is lacking in the literature.

Conservation tillage can be defined as tillage leaving behind at least 30% of the crop residue on the soil surface (Tiessen et al., 2010). The benefits of conservation tillage are widely documented, including reducing erosion and building soil health (Lozano-Garcia and Parras-Alcantara, 2014; Rahman et al., 2008; Baker et al., 2006; Ismael et al., 1994). However, several studies report that poorly drained soils may not respond to conservation tillage practices as effectively as well-drained soils in positively preventing soil erosion and improving soil conditions and crop yield (Dick and Van Doren, 1985; Christov et al., 1982; Griffith et al., 1973). Soils of the RRV region are high in clay content, have high soil water holding capacities, and are poorly drained (Soil Survey Staff, 1999). Occurrences of decreased crop yields under NT have therefore discouraged producers from reducing soil tillage operations (Afzalinia and Zabihi, 2014). Despite these poor drainage conditions that limit the number of days with good trafficability during field operations, the smectitic mineralogy of the RRV soils has added benefits of shrinking, swelling, and cracking to alleviate soil penetration resistance in cropped fields (Gajri et al., 2002). Therefore, soil penetration resistance due to tillage or the lack of tillage on these soils may only be a detriment to crop production for a brief time (e.g., until soil drying induces cracks to form and alleviate compacted soil layers).

Reduced tillage implements that are frequently of interest in the RRV, for producers hesitant of NT practices, include chisel plow (CP), shallow vertical tillage (VT), strip tillage with coulters (STC), and strip tillage with shanks (STS). In general, less intensity of soil disturbance via tillage results in less soil erosion and water loss (Reicosky, 2015; Soil Science Glossary Terms Committee, 2008). Strip tillage provides an opportunity to reduce tillage by limiting the total surface area tilled, thereby leaving surface crop residue in place (Baker et al., 2006; Campbell et al., 1996). Some research classifies ST as a moderate intermediary to both conventional tillage and NT, leaving a limited amount of soil residue and a portion of undisturbed soil in between narrow tillage rows (Baker et al., 2006). In general, STC and STS vary based on the tool used within the row during tillage. The purpose of VT is to cut through, size, and mix crop residue, resulting in varying crop residue amounts on the soil surface (Nowatzki, 2013; Klingberg and Weisenbeck, 2011). Vertical tillage adoption has significantly increased in North Dakota over the last five years (Nowatzki, 2013) and this practice can include the use of many types of implements. Tillage using a CP is the least conservative of these practices since it incorporates most of the crop residue into the soil while using more intense tillage components including varying sweeps, spikes, and shovels with additional options of twists and angles (Reicosky, 2015). The choice of a tillage practice a producer may implement varies depending upon multiple factors. Soil texture, soil depth, crop, climate, and socioeconomic sources are among the reasons of selecting a suitable reduced or conservation tillage practice (Gajri et al., 2002).

Researchers have examined various reduced tillage practices and have reported mixed effects on soil physical conditions and crop yields; citing variations in site-specific field condition (Licht and Al-Kaisi, 2005a; Al-Kaisi and Hanna, 2002; Hussain et al., 1999; Ismael et al., 1994). On average, conventional tillage systems have shown soil temperatures to be higher than NT systems (Gauer et al, 1982; Mock and Erbach, 1977; Lal, 1974). Soil warming is known to be slower in NT and in some reduced tillage practices due to additional crop residue coverage of the soil. The crop residues can reflect a portion of solar radiation and the underlying undisturbed soil has a higher thermal conductivity than tilled soil, which spreads out heat deeper in the soil with smaller changes in temperature in the seedbed (Johnson and Lowery, 1985; Mock and Erbach, 1977; Moody et al., 1963; Burrows and Larson, 1962; van Wijk et al., 1959). Moody et al. (1963) determined that soil mulches slowed the soil warming, but also observed benefits for crop growth and yield when compared with bare soils during dry years. Kargas et al. (2012) and Su et al. (2007) have reported similar results. Griffith et al. (1973) examined ST operations versus conventional tillage practices and determined that in-row soil temperatures were higher for ST as compared with NT practices, but less warm than conventional tillage practices. A study by Rasmussen (1999) examined soil temperature and evaporation in fields under conservation tillage in the Scandinavian countries of Denmark, Finland, Norway and Sweden. Results indicated a reduced evaporation rate, linked to a lower soil temperature of land under conservation tillage. Radke (1982) concluded that wet soil has a greater heat capacity than dry soil and that energy inputs to the soil surface may often be partitioned more into the latent heat of evaporation, rather than storage for warming the soil.

Some studies have indicated increased crop yields under reduced tillage practices when compared to conventional practices (Pedersen and Lauer, 2003; Hussain et al., 1999; Norwood, 1999; Dickey et al., 1994; Ismael et al., 1994). Others have noted decreases in crop yields under reduced tillage practices, though not always statistically significant (Salem et al., 2015; Pedersen and Lauer, 2003; Hoeft et al., 2000; Vyn and Raimbault, 1992). Daigh et al. (2017) investigated the effect of NT and CP tillage practices in long-term (8-51 years) rotated corn-soybean and continuous corn-corn fields at eight field sites across the Midwestern US corn-belt. For continuous corn and the corn phase of corn-soybean rotation, they concluded slight differences in yield for the varying practices (favoring CP), but noted some benefits to NT during periods of drought. During the soybean phase of the corn-soybean rotation, no significant differences in yield were observed for any site-year. Conservation tillage in the Upper Great Plains is sensitive to climatic conditions, soil properties, cropping systems, and needs of conserving soil moisture while reducing wind and water erosion (Carter, 1994). Pedersen and Lauer (2003) and Vetsch and Randall (2002) examined crop yields under NT in Wisconsin and Minnesota, respectively, and concluded that in a northern temperature climate, cropland under NT can demonstrate a reduced yield due to reduced soil temperature and subsequent delayed crop emergence. However, Buman et al. (2004) examined variations in crop production and soil properties in corn-soybean fields under ST and NT practices as compared to conventional tillage at 13 field sites across Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Michigan, and Ohio. When observing crop emergence, no significant differences were report among varying tillage practices. Similar results were also reported by Vetsch and Randall (2002) in Minnesota for continuous corn-corn and rotated corn-soybean fields with CP and ST. The crops under CP in continuous corn-corn fields emerged $\leq$ 1 day faster as compared with ST practices, and were not significantly different. Crops yields were less than 3% among all tillage treatments in the continuous corn-corn fields. No significant differences in yields were observed in rotated corn-soybean fields.

Climate conditions play a role in determining which tillage practices are appropriate for individual cropping systems. However, mixed results are reported in the literature for regions with frigid soils. In a frigid environment, we hypothesize that there is significant differences among reduced tillage treatments based on soil temperatures and volumetric water contents, but that these effects on soil warming and drying do not often translate into differences in crop yields. Instead, crop yield differences are expected to be functions of whether soil nutrients were adequately delivered to the crop or soil smearing during tillage. Additionally, there is no published research from the RRV in eastern North Dakota and western Minnesota on conservation tillage implement's effects across a wide range of soil textures accompanied by detailed measurements of soil physical conditions and chemical properties, along with crop yields using full-sized equipment in producer's fields. The North Dakota climate is subject to short growing seasons; therefore, an understanding on the relationship between soil warming and soil texture may aid North Dakota farmers in making best management decisions. Our objectives were to evaluate the effects of CP, VT, STC, and STS implements on soil physical conditions and properties, soil chemical properties, and crop performance and yields among a wide range of soil textures in a frigid environment.

Materials and Methods

Site Description

Replicated soil tillage treatments were installed on three producer farms near Mooreton, ND, Barney, ND, and Fergus Falls, MN (Figure 1). All sites were located on privately owned farms, where producers performed all production operations. All soil series at the three farms are frigid, meaning the average annual temperature of the soil falls below 8 ℃. Topsoil textures at the three farms ranged from fine sandy loams at the Barney farm, loams and clay loams at the Fergus Falls farm, and silty clays at the Mooreton farm (Table 1).

Soils at the Mooreton farm are on glacial lacustrine sediments, the Barney farm on a beach line of the ancient glacial Lake Agassiz, and the Fergus Falls farm on glacial till (Thorleifson, 1996). These glacial derived soils contain significant quantities of smectite clays that cause substantial soil shrinkage and cracking during dry conditions (Brierley et al., 2011).

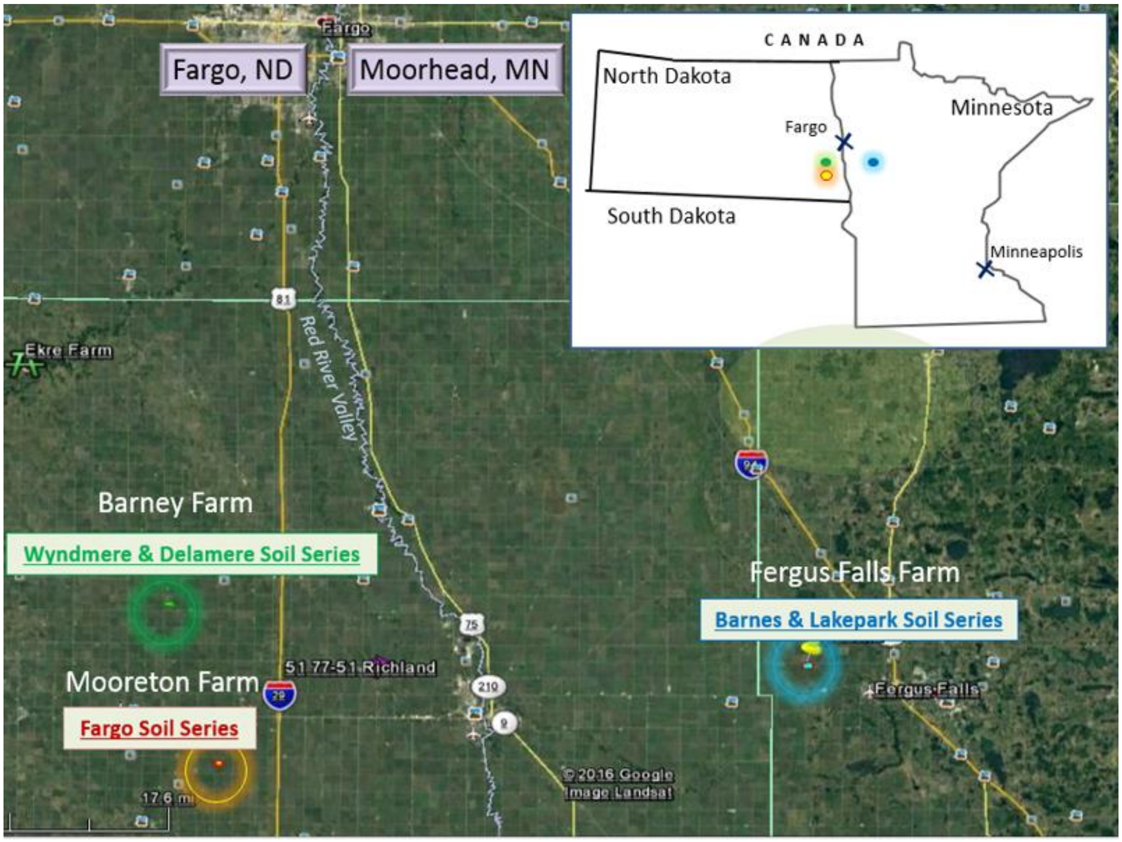

Figure 1. Field site locations and soil series in Mooreton, ND (Fargo soil series), Barney, ND (Wyndmere and Delamere soil series), and Fergus Falls, MN (Barnes and Lakepark soil series).

Table 1. Soil taxonomical information and characteristics of three farm locations in North Dakota and Minnesota

Location	Soil series	Soil classification	Dominant soil texture	Geographic extent (hectares)
Mooreton, ND	Fargo clay	Fine, smectic, frigid Typic Epiauerts	Silty Clay	3.8 million
Barney, ND	Wyndmere	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls	Fine Sandy Loam	1 million
	Delamere	Coarse-loamy, mixed, superactive, frigid Typic Endoaquolls	Fine Sandy Loam	204,747
Fergus Falls, MN	Lakepark	Fine-loamy, mixed, superactive, frigid Cumulic Endoaquolls	Clay Loam	168,325
	Barnes	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls	Loam	15.2 million

The Mooreton farm's soil is a Fargo silty clay soil series (fine, smectitic, frigid Typic Epiaquerts) with a geographical extent of 3.8 million hectares of production agriculture in the U.S. Fargo soil series are deep and have a high water holding capacity with poor drainage (USDA and SCS, 1975). Therefore, these soils often flood in the spring following snowmelt and after large rainfall events. To remove excess soil water, many produces install surface or subsurface (i.e., often referred to as tiles) drainage systems. The Mooreton farm currently has numerous ongoing research projects that focus on subsurface drainage, soil salinity (Thapa et al., 2017), and cover crops. The northern half of the farm is subsurface drained at a 1.1 meter depth and 12.1 m spacing between drainage laterals; whereas, the southern half has no current or history of subsurface drainage. Surface drainage is used on both the northern and southern halves to alleviate prolonged ponding of springtime snowmelt. The site also has a soil salinity gradient due to a saline seep, with saline soils at the field's western edge that dissipates to the east along the field. Because of this, the Mooreton farm was divided into quadrants with various combinations of water management and saline conditions. In other words, the NW quadrant is surface- and subsurface-drained saline soils, the NE quadrant is surface- and subsurface-drained nonsaline soils, the SW quadrant is surface-drained saline soils, and the SE quadrant is surface-drained nonsaline soils (Figure 2).

The Barney farm has two dominant soils, Wyndmere (coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls) and Delamere (coarse-loamy, mixed, superactive, frigid Typic Endoaquolls) soil series, with a combined geographical extent of nearly 1.2 million hectares of production agriculture in the U.S. Both soil series at the Barney farm are fine sandy loam in texture. These are nearly leveled, deep, and contain mottled and gleyed soil horizons at 65 cm depth indicating poor drainage in the soil. Both these series at this site are superactive, meaning they possess a high cation exchange capacity (CEC), which is due to the smectitic mineralogy of their clay content. As calciaquolls, they are rich in calcium or gypsum in the topsoil. Wyndmere and Delamere soil series contain limited cracks in the topsoil due to the low clay content (Soil Survey Staff, 1999).

Figure 2. Mooreton, ND farm site design in quadrants with the NW surface- and subsurface-drained saline soils, NE surface- and subsurface-drained nonsaline soils, SW surface-drained saline soils, and SE surface-drained nonsaline soils.

The Fergus Falls farm has two dominant soils, Lakepark (fine-loamy, mixed, superactive, frigid Cumulic Endoaquolls) and Barnes (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) soil series, with a combined geographical extent of nearly 15.2 million hectares of production agriculture in the U.S. (USDA and SCS, 1975). Lakepark soil series dominant soil texture is clay loam and is poorly drained. Whereas the Barnes soil soils dominant soil texture is loam and is well-drained. Lakepark soil series are generally deep and it is formed by colluvium which is a result of gravity moving water or wind into a shallow slope. Lakepark soil typically forms in floodplains or a closed depression.

Experimental Design, Treatments, and Field Management

Tillage treatments at each of the three farms were arranged in a randomized complete block design with each tillage treatment replicated three times. Each of the three farms had corn-soybean rotations with one phase of the two-year rotation grown each year. Tillage plots were 12.2 meters wide and extended the full length of the field (i.e. 480 m to 560 m in length). Tillage treatments included a shallow vertical tillage (VT), strip tillage with shanks (STS), strip tillage with coulters (STC), and chisel plowing (CP) in which full-sized field implements were used. At the Fergus Falls and Barney farms, soil series were identified and measurement/sampling transects across all tillage treatments and their replicates were established. At the Mooreton farm, measurement/sampling transects were established in each of the four quadrants (Figure 2). Similar to the transects established at the Fergus Falls and Barney farms, the transects at the Mooreton farm were set across all tillage treatments and their replicates.

The CP treatment was plowed in the fall (one pass) at a depth of 18-20 cm with twisted shovels and then was field cultivated in the spring before planting each year. The VT treatment was tilled in the fall (one pass) and then again in the spring (one pass) at a depth of 2-8 cm, with disc gangs set a 3-4° and coulters spaced 15 cm apart which was followed by harrows and rollers. The STS treatments were applied in the fall (one pass) whereas STC treatments were applied in the spring (one pass) using wavy/fluted coulters. Both STS and STC were tilled to a depth of 18-20 cm and 13-15 cm, respectively, with spacing of 76 cm. Both STS and STC implements had a front opening coulter to cut through crop residue and open the soil surface, residue managers to sweep the crop residue away from the tilling shank or coulter, a fertilizer injector, covering disc to form a berm of the tilled soil, and then a narrow harrow or roller to firm the tilled soil berm. Crop seeds were planted in the tilled soil berms during spring planting. For both STS and STC treatments, the crop residue and soil in-between the plant rows were left mechanically untouched (i.e. strips of no-till). In 2016, the tilled plant rows for both STS and STC were shifted approximately 8 cm to the side of the 2015 plant rows to eliminate issues with planting into corn root balls.

Site Management

Over the past 30 years, each farm had a crop history of corn, soybean, and/or wheat rotations. At the Fergus Falls farm, chisel plow was the primary tillage practice during the previous 10 years. At the Barney farm, field cultivation was the primary tillage practice prior to planting corn whereas NT was used prior to planting soybeans during the previous 10 years. At the Mooreton farm, disk ripper was the primary tillage practice used for corn and wheat, while chisel plow followed by field cultivation was used for soybean over the last 30 years. At the Barney and Fergus Falls farms in 2015, corn crop was planted on May 2nd and harvested on October 5th. At the Barney farm in 2016, soybean crop was planted on May 9th and harvested on September 9th. At the Fergus Falls farm in 2016, soybean crop was planted on May 25th and harvested on September 28th. At the Mooreton farm in 2016, corn crop was planted on May 5th and harvested on October 18th.

Soil fertilizer was applied based on soil test results and standard fertilizer recommendations for the soil textures within the region. All crops were planted in 76 cm spaced rows for each farm and year. Weeds and pests were also controlled by the producers based on standard regional recommendations. Fertilizer placement varied based on tillage practice. For CP treatments, fertilizers were broadcasted in the spring and then incorporated into the soil with the field cultivator. For the VT treatments, fertilizers were broadcasted in the spring and then incorporated with the spring VT pass. For both STS and STC treatments, fertilizer was banded at a 5-10 cm depth at the time of tillage through the implement's fertilizer injector. Nitrogen fertilizers used included urea and ammonium nitrate at all three farms. The Barney producer split applied nitrogen; starter nitrogen prior to planting with a second nitrogen application as side dressed anhydrous ammonia at the onset of corn's rapid growth stages. Corn stalks were rolled prior to the planting of soybean at all sites.

Field Monitoring and Sample Collection

<u>Soil Temperatures and Volumetric Water Contents (Handheld Measurements)</u>

Soil volumetric water contents (θ) and soil temperatures (T) were measured near the soil surface via biweekly readings with handheld sensors in 2015 and 2016 at each farm and at each sampling transect. Measurements were taken from pre-planting through post-harvest at all three farms. Soil θ and T measurements were taken in 2015 and 2016 for the Barney and Fergus Falls farms and in 2016 for the Mooreton farm. Measurements were taken in the Wyndmere and Delamere soil series sampling transects at the Barney farm, in the Barnes and Lakepark soil series sampling transects at the Fergus Falls farm, and in the Fargo soil series sampling transection with surface drainage ditches and nonsaline soil at the Mooreton farm.

Among the three farms, biweekly soil θ and T measurements were taken between DOY 76 and DOY 283 in 2015 and between DOY 58 and DOY 274 in 2016 while soils were not frozen for a total of 24,624 measurements at depth across all farms. Soil θ was measured using Decagon GS3 sensors with ProCheck meters. Soil T was measured using a nickel-chromium (type K) thermocouple probe with a digital display. Immediately before each soil θ and T measurement, the crop residue was moved and the soil's mineral surface was exposed. The GS3 sensor's needles was then vertically inserted normal to the soil surface. Then, soil T was measured at 0.5, 2, 5, and 12 cm depths with the thermocouple out of direct sunlight. Soil θ and

T were taken in triplicate for each plot for both CP and VT treatments. In both STS and STC treatments, soil θ and T was measured in triplicate for both the tilled soil strip and in the between areas (i.e., zones untouched by tillage) (i.e., n=6 for each plot for both STS and STC). These measurements taken in triplicate for each experimental plots and strip tillage zone allows for period, but relatively high spatial representation of soil θ and T in these producer's fields. At conclusion of all measurements, crop residue was placed back to where it was initially removed.

Soil Temperatures and Volumetric Water Contents (Near Continuous Measurements)

In order to supplement the spatial representativeness of soil θ and T obtained by the biweekly handheld measurements, where one monitoring station was delpoyed in each plots of two blocks for one transect at each farm to monitor soil θ and T on a near-continuous basis using Decagon 5TM sensors with Em50 dataloggers for a total of 3.9 million measurements at depth across all farms. Prior to field deployment, soil sensors were calibrated in the laboratory with soils collected from each of the three farms. Once calibrations were obtained for each soil series and each 5TM sensor, the sensors were deployed in the field at 5, 10, 25, and 40 cm depths with measurements recorded at 30-minute intervals. Both STS and STC treatments had sensors deployed in and between the tilled strips. Due to the monetary expense of the soil θ and T monitoring systems, sensors were deployed in two of the three replicates at each of the three farms (Figure 3). Soil θ and T were monitored at the Mooreton farm in the surface-drained nonsaline soil quadrant of the Fargo soil series starting in the fall of 2015. At the Barney farm, soil θ and T were monitored in the Wyndmere soil series transect starting in the fall of 2015. At the Fergus Falls farm, soil θ and T were monitored in the Barnes soil series transect starting in the spring of 2016.

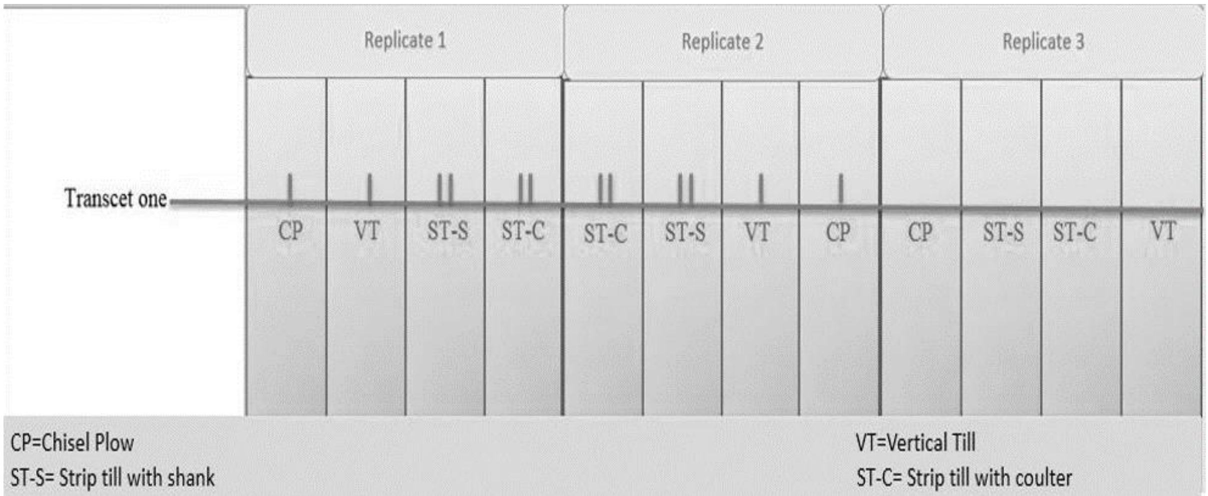

Figure 3. Soil θ and T monitoring systems deployment in a monitoring transect. Dashes along the transect in replicates 1 and 2 indicate where monitoring systems were installed. One monitoring system was deployed in both the CP and VT treatments whereas and 2 monitoring systems were deployed in and between the tilled strips in both STC and STS treatments.

Soil Penetration Resistance Measurements

Soil penetration resistance was measured using a FieldScout CS 900 static cone penetrometer (Spectrum Technologies, Inc., Aurora, IL) during 2016 for all soil series at the Barney and Fergus Falls farms and for the surface-drained nonsaline soils at the Mooreton farm. Soil penetration resistance was measured at 2.5 cm increments to a depth of 45 cm. Soil penetration resistance was measured in triplicate for each plot for both CP and VT treatments. In both STS and STC treatments, soil penetration resistance was measured in triplicate for both the tilled soil strip and in the between areas (i.e., zones untouched by tillage) (i.e., n=6 for each plot for both STS and STC). Measurements were taken three times during the 2016 growing seasons: near planting (~DOY 135), shortly after full canopy (~DOY 208) and near harvesting (~DOY 290) for a total of 5,832 measurements at depth across all farms.

Soil Chemical Properties Measurements

Soil samples were collected during June in 2015 and 2016 for chemical analysis. In 2015, soil samples were collected from 0-15 cm depth for both soil series at each of the Barney and

Fergus Falls farms for a total of 216 samples. In 2016, soil samples collected from two depths of 0-15 cm and 15-30 cm for both soil series at each of the Barney and Fergus Falls farms and for all four quadrants at the Mooreton farm for a total of 864 samples. Samples were collected from the tilled zones; however, not specific to the seedbed. Soil samples were air dried, ground, and analyzed for NO_3-N, NH_4-N, Olsen soil test P, K, S, Zn, Fe, Mn, Cu, Ca, Mg, and Na. A 50 g subsample was ground to pass through a 0.250 mm sieve and analyzed for total carbon (TC) and inorganic carbon (IC) using a Primacs[SLC] TOC analyzer; the differences in TC and IC was used to estimate total organic carbon (TOC) concentrations.

Crop Residue, Plant Metrics, and Crop Yields

Percent crop residue cover of the soil surface, plant population counts, and plant heights were measured during the corn V3 growth stage at Barney and Fergus Falls farms in 2015 and 2016 and in all 4 quadrants at the Mooreton farm in 2016. The percent crop residue cover was determined using a 5.3 m chain with equally spaced knots, equal to .0004 of a hectare. Under each chain knot, crop residue was determined as present or not. Plant population counts were measured by the line-transect method (Hill et al., 1989; Sloneker and Moldenhauer, 1977). Plant heights were measured by using free standing plants where a meter stick was used to measure from the soil surface to uppermost leaf tip and was repeated ten times to measure adjacent plants that were representative of the entire transect. The method was repeated three times per treatment, per plot, and per transect. Percent crop residue cover, plant population counts, and plant heights were measured in triplicate for each plot at all farms. Crop yield measurements were taken for the center eight crop rows for each plot at each farm in 2015 and 2016 via weigh wagons and combine yield monitor data.

Statistical Analyses

A repeated measures mixed model analysis of variance (ANOVA) was used to determine the effects of tillage, date, depth, and their interactions on the handheld soil T measurements. Measurement date and depth were both set as repeated measures with compound symmetry covariance structure. The handheld soil θ data was also measured with the same repeated measures mixed model ANOVA with the exclusion of the depth main effect and interactions and depth repeated measures command. To analyze the near-continuous soil T and θ datasets, the 30-minute interval data was first summarized by calculating daily mean soil T and θ as well as daily maximum and minimum soil T. These daily summarized values were then analyzed similar to the handheld soil T measurements using a repeated measures mixed model ANOVA with date and depth as repeated measures and compound symmetry covariate structures. However, due to the computational intensity and long run times (i.e., > 4 days) to analyzed these daily values (i.e., hundreds of treatment levels in the date main effect and date interactions with tillage treatment and depth), the datasets were divided into months and each month for each soil series sampling transect was analyzed separately. Due to some issues with datalogging at the Barney farm resulting in missing data, the near-continuous soil T and θ data could not be statistically separated due to missing data causing issues with estimating treatment means. A repeated measures mixed model ANOVA was used to determine the effects of tillage, date, depth, and their interactions on soil penetration resistance. Measurement depth was set as repeated measures with compound symmetry covariance structure. A mixed model ANOVA was used to determine the effects of tillage, depth, and their interaction on soil chemical properties. Crop residue cover, plant height, population counts, and crop yields were all analyzed using a mixed model ANOVA to determine effects of tillage. All soil and crop parameters in each model was analyzed individually for each soil series sampling transect at each farm since data was not always measured on the same dates within each parameter. Means for each parameter were separated using Tukey's Honest Significant Difference (HSD) test at an alpha level of 0.05 and all analyses were performed using SAS version 9.4.

Results

Crop Residue Cover

As expected, crop residue cover was significantly affected by tillage practice at all three farms in both 2015 and 2016 (Table 2). In 2015 and 2016, the CP resulted in significantly lower crop residue cover as compared to VT, STC, and STS at the Barney and Fergus Falls farms. In 2016, VT also had significantly higher crop residue cover as compared to STC and STS (79 vs. 68 and 65%, respectively). At the Mooreton farm Fargo-SE and Fargo-SW soil series transects showed no significant difference in crop residue coverage in 2016 under a corn crop phase. In 2016, the Mooreton farm Fargo-NE soil series transect showed a significantly lower amount of crop residue in CP as compared to VT, STC, and STS tillage practices (i.e., 28 vs. 33, 42, and 32 percent, respectively). In 2016, CP resulted in significantly lower crop residue cover as compared to VT, STC, and STS on the surface- and subsurface-drained saline soil (i.e., NW quadrant) and surface- and subsurface-drained nonsaline soil (i.e., NE quadrant) at the Mooreton farm. Tillage did not significantly affect crop residue cover on the surface-drained saline (i.e., SW quadrant) and surface-drained nonsaline soil (i.e., SE quadrant), although mean values were numerically lowest in the CP treatments (Table 2).

Table 2. Crop residue cover (%) under reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter (STC), and strip tillage with shank (STS)] at Mooreton, ND, Fergus Falls, MN and Barney, ND farms in 2015 and 2016.

Year	Farm	Crop Phase	CP	VT	STC	STS
2015	Barney	Corn	25b†	49a	51a	50a
	Fergus Falls	Corn	42b‡	60a	52a	48a
	Mooreton	NA	NA	NA	NA	NA
2016	Barney	Soybean	31b	61a	52a	60a
	Fergus Falls	Soybean	50c	79a	68b	65b
	Mooreton-NE	Corn	28b	33a	42a	32a
	Mooreton-SE	Corn	19a	44a	48a	32a
	Mooreton-NW	Corn	15c	42a	42a	28b
	Mooreton-SW	Corn	33a	43a	51a	41a

†Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.
‡ NA-Not Available

Soil Temperatures and Soil Volumetric Water Contents

Handheld Measurements

In 2015 and 2016, a significant three-way interaction among tillage, date, and depth was evident at the Barney, Fergus Falls, and Mooreton farms (Appendix A1). Results on dates and depths (i.e., 0.5, 2, 5, and 12 cm) when soil T was affected by tillage practices are displayed for Barney (Table 3), Fergus Falls (Table 4), and Mooreton (Table 5) farms for 2015 and 2016. Across all farms, differences in soil T due to tillage were evident at various times throughout the annual observation periods (i.e., when soils were not frozen). Generally, few or no differences were observed between mean soil T in CP, STC-IN, and STS-IN tillage practices and between mean soil T in the VT, STC-BT and STS-BT tillage practices for all farms and soil depths.

Table 3. Summary of the mean soil temperature for dates that handheld measurements for the Barney farm in the Wyndmere and Delamere soil series sampling transects in 2015 and 2016 and depths were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT)].

Farm	Date	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	----------------------------------			°C		----------------------------------
Barney	3/17/2015	0.5	13.5a†	3.2b	12.7a	3.7b	11.2a	3.6b
		2	12.4a	3.6b	7.9a	4.0b	7.5ab	3.9b
	4/03/2015	0.5	9.7a	3.3b	8.9a	4.2ab	8.3ab	4.1b
	4/23/2015	0.5	12.1a	2.1b	9.5a	4.4ab	10.8a	3.8b
		2	10.2a	0.2b	8.5a	1.4b	8.0a	1.0b
		5	6.2a	-0.6b	5.5a	-0.1b	4.1a	0.0b
		12	5.8a	-0.6b	5.9a	-0.1b	4.0a	-0.1b
	6/03/2015	5	12.7a	8.1b	11.5a	9.0b	11.0a	8.7b
	7/09/2015	0.5	42.4a	34.8b	36.8ab	35.4b	37.4ab	36.9ab
		5	35.1a	27.9b	31.0a	28.9b	30.0ab	28.4b
	7/19/2015	0.5	37.4a	27.7b	33.8a	27.5b	33.1a	28.1b
		2	38.4a	30.4b	32.2ab	31.0b	31.0b	31.0b
	8/26/2015	12	19.9a	17.6b	17.9ab	17.6b	18.1ab	18.0ab
	3/11/2016	0.5	17.2a	9.1b	9.0b	12.9ab	6.3b	15.9a
		2	12.8a	4.9b	9.0a	5.6b	11.4a	3.4b
		5	6.2a	2.4b	4.9a	2.8b	5.6a	1.7b
	3/28/2016	0.5	15a	3.2b	10.3a	3.9b	9.1a	3.8b
		5	2.3a	0.9b	2.6a	2.0a	2.3a	1.7ab
	5/04/2016	0.5	33.6a	27.3ab	30.2a	21.0b	34.2a	19.3b
		2	32.0a	23.0b	24.3ab	18.1b	31.1a	17.6b
		5	27.1a	19.0b	20.1a	16.8b	24.6a	16.4b
		12	27.9a	20.9b	22.7a	17.8b	26.9a	17.0b
	5/14/2016	0.5	23.1a	14.1b	18.4a	11.3b	19.9a	13.9b
		2	20.6a	12b	12.3b	10.3b	19.7a	11.6b
		5	15.1a	9.4b	12.7a	9.1b	14.7a	9.9b
	6/02/2016	0.5	24.7a	18.4b	22.8a	18.5b	21.1a	18.1b
	6/16/2016	0.5	33.0a	23.3b	27.1a	23.5b	26.6a	23.1b
	7/04/2016	0.5	45.6a	34.0b	35.5b	34.6b	33.1b	36.3b
		2	42.9a	30.4b	33.4ab	31.6b	30.9b	34.4ab
		12	38.2a	28.3b	30.2a	29.5ab	31.2a	28.5b
	8/09/2016	0.5	26.2a	19.9b	23.2ab	22.1b	22.1b	21.4ab
		2	24.5a	19.2b	20.6ab	20.4ab	20.5ab	20.2ab
		5	22.1a	18.3b	19.4ab	19.4ab	19.4ab	19.2ab

†Different letters within a row are significantly different at the 0.5 level using Tukey's HSD test.

Table 4. Summary of the mean soil temperature for dates that handheld measurements for the Fergus Falls farm in the Barnes and Lakepark soil series sampling transects in 2015 and 2016 and depths were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT)].

Farm	Date	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	°C					
Fergus Falls	4/27/2015	2	17.9a†	13.1b	17.0a	11.3b	16.8a	12.8b
	6/10/2015	0.5	33.8a	28.0b	32.7a	30.0a	32.3a	29.5ab
	7/21/2015	0.5	32.7a	29.7ab	31.5a	28.7b	32.0a	29.0b
		5	24.55a	21.45b	23.59a	21.34b	23.17a	20.90b
		12	25.6a	21.9b	24.0ab	22.60b	25.11a	22.84b
	8/27/2015	12	20.6a	16.7b	16.9b	16.8b	16.9b	16.8b
	4/04/2016	0.5	13.3a	10.4a	11.8a	3.1b	10.3a	1.6b
		2	3.9a	2.8a	5.4a	1.1b	3.7a	0b
	4/16/2016	0.5	24.2a	14.7ab	14.9ab	12.8b	15.9ab	12.1b
		2	16.9a	11.6b	12.4ab	10.5b	12.3ab	10.9b
	5/05/2016	0.5	37.6a	29.24ab	32.8ab	24.6b	33.4a	26.1b
		5	25.34a	16.2b	17.61a	16.4b	19.52a	17.3ab
		12	16.4a	11.7b	14.3a	12.5b	14.8a	12.5b
	5/19/2016	0.5	19.6a	12.9b	17.6a	13.3b	18.1a	13.3b
		2	18.1a	12.0b	14.8a	12.7ab	15.7a	12.7ab
		5	14.5a	11.5b	21.0a	17.4ab	21.4a	16.6ab
	6/05/2016	0.5	30.0a	19.7b	27.3a	21.2b	29.0a	19.7b
		2	28.2a	18.3b	25.4a	23.1b	27.4a	18.5b
		5	23.7a	16.3b	21.0a	17.4b	21.4a	16.6b
	7/02/2016	0.5	33.8a	27.9b	30.7a	28.6b	30.6a	28.3b
		2	32.0a	26.7b	29.4a	27.5b	29.1a	27.3b
		5	29.3a	23.9b	26.6a	25.6a	26.3a	25.1ab
	8/05/2016	0.5	31.2a	26.6b	29.4a	28.5b	30.0a	29.8b
		2	30.5a	25.8b	27.7ab	27.6ab	28.1ab	27.7ab
		5	19.9a	19.6ab	19.4b	19.4b	19.5ab	19.6ab

Table 5. Summary of the mean soil temperature for dates that handheld measurements for the Mooreton farm in the Fargo NE soil series sampling transects in 2016 and depths were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT)].

Farm	Date	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	-------------------------------------°C-------------------------------------					
Mooreton	3/14/2016	0.5	17.1a†	14.0a	16.0a	11.0b	12.44ab	12.1b
		12	9.6a	6.9b	9.3a	9.0ab	9.6a	9.4a
	3/28/2016	0.5	14.0a	14.0b	14.2ab	12.9b	15.3a	13.8b
		12	5.7a	4.0b	5.2a	3.5b	4.3ab	3.8b
	4/15/2016	0.5	16.2a	13.9b	14.3ab	12.9b	15.3a	13.8ab
	5/04/2016	0.5	35.4a	32.1a	30.8a	24.3b	33.2a	27.6b
		2	31.4a	27.6a	26.8a	22.2b	28.8a	25.8ab
		5	25.0a	22.0b	22.8a	19.3b	23.1a	21.9b
		12	28.3a	24.2b	24.1b	20.8b	26.0a	23.5b
	6/16/2016	0.5	27.7a	23.5b	24.5a	23.2b	25.2a	23.6b
		2	27.0a	22.5b	23.3b	22.3b	24.4a	22.7b
		5	23.9a	19.7b	21.8a	20.0b	20.1ab	18.9b
	7/05/2016	0.5	33.7a	29.3b	30.7a	29.4b	31.4a	30.1ab

† Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

Soil T at multiple depths did not differ among the CP, STC-IN, and STS-IN zones throughout 2015 and 2016 with only a few exceptions where CP was significantly higher, most notable in July (Figures 4, 5, 6, 7 and 8). However, the soil temperatures in CP, STC-IN, and STS-IN were typically significantly higher at multiples depths than VT, STC-BT, and STS-BT, which did not differ among each other. When tillage effects were evident, the CP, STC-IN, and STS-IN mean soil temperatures generally ranged from 2 to 10°C higher than the VT, STC-BT, and STS-BT treatments. Tillage effects were most often observed near the soil surface (0.5 and 2 cm) with less effects observed in the 5 cm soil depth and with few differences observed at the 12 cm soil depth. At the 12 cm soil depth, tillage practices significantly affected soil temperatures 12 times across all farms for the 19 total dates in 2015 and 2016 when handheld sensor measurement were obtained. When significantly different, CP and VT differences were most frequently observed.

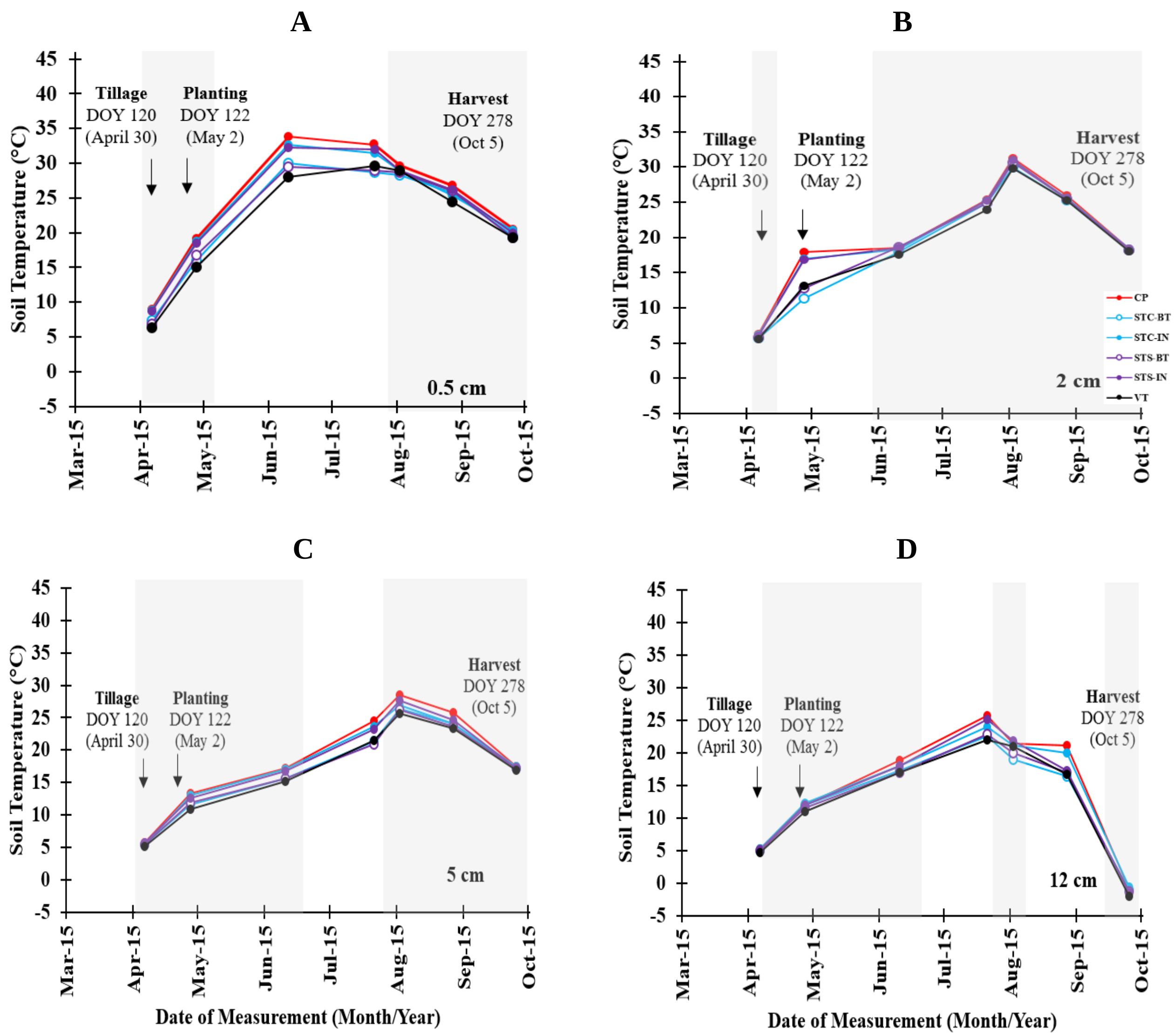

Figure 4. Handheld measurements for soil temperatures at the Fergus Falls farm (Lakepark soil series sampling transect) at the 0.5 cm (A), 2 cm (B), 5 cm (C), and 12 cm (D) soil depths during 2015. Shaded areas indicate periods of no significant differences among tillage practices.

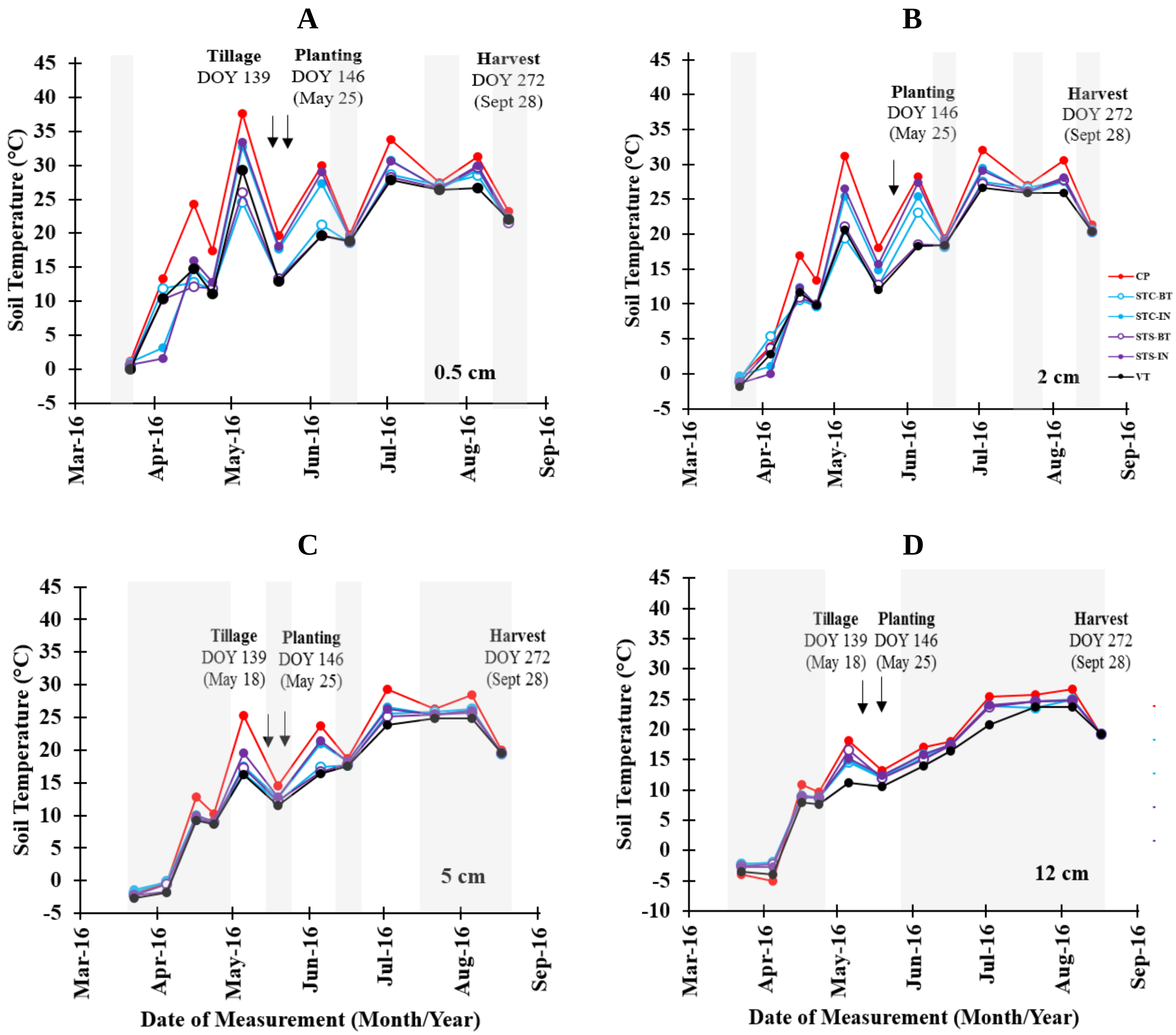

Figure 5. Handheld measurements for soil temperatures at the Fergus Falls farm (Lakepark soil series sampling transect) at the 0.5 cm (A), 2 cm (B), 5 cm(C), and 12 cm (D) soil depths during 2016. Shaded areas indicate periods of no significant differences among tillage practices.

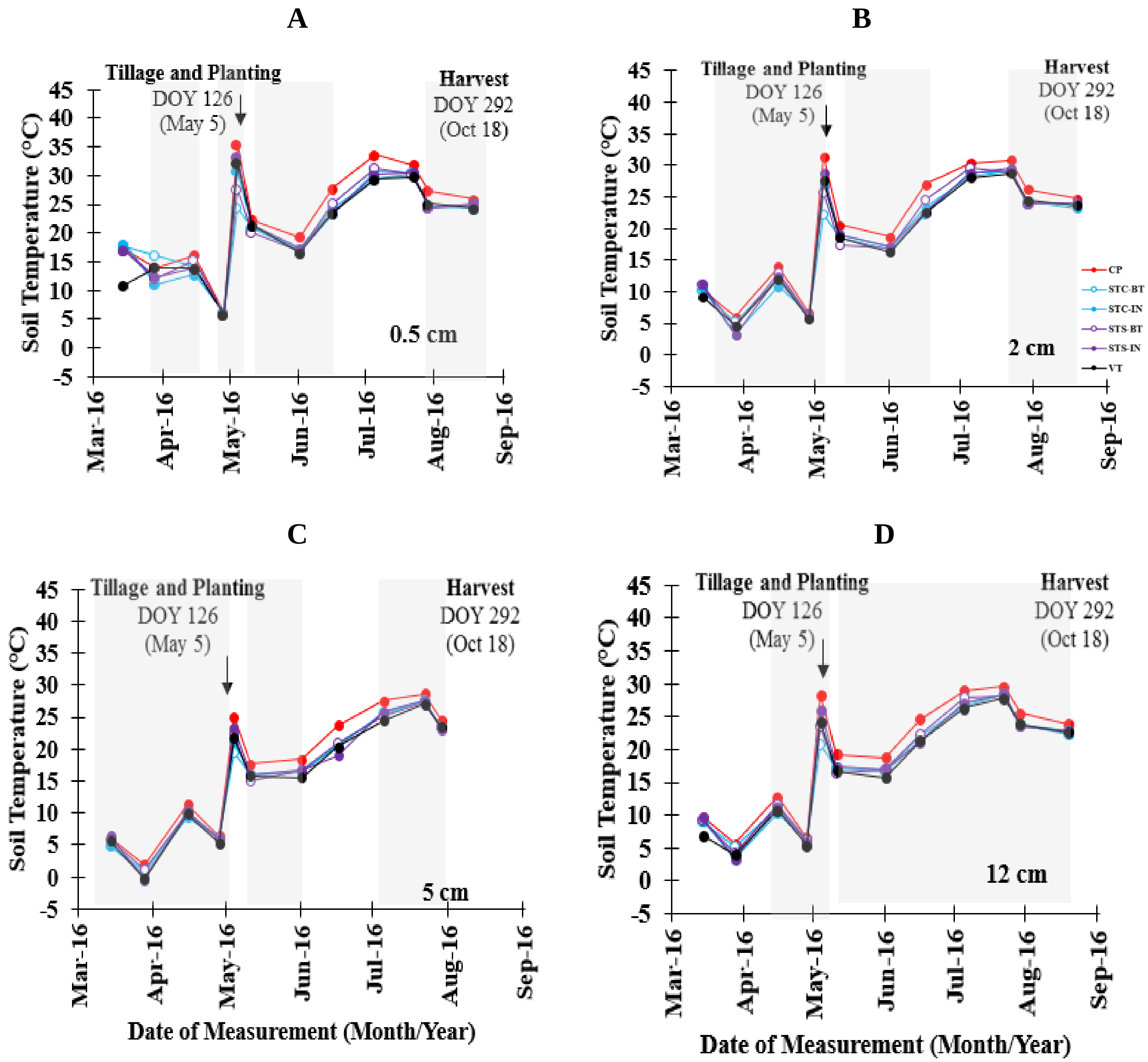

Figure 6. Handheld measurements for soil temperatures at the Mooreton farm Fargo Clay NE soil series sampling transect at the 0.5 cm (A), 2 cm (B), 5 cm(C), and 12 cm (D) soil depths during 2016. Shaded areas indicate periods of no significant differences among tillage practices.

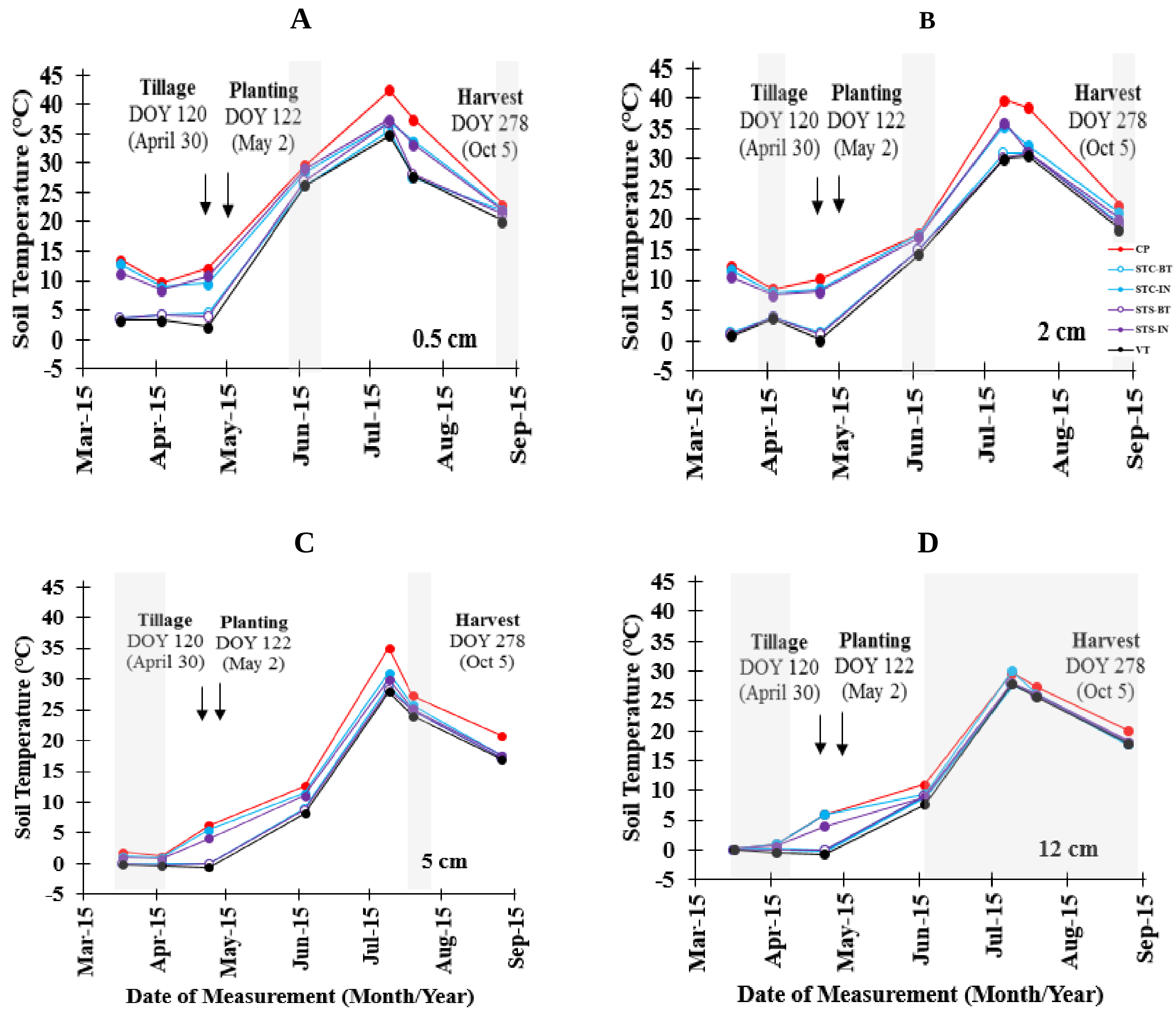

Figure 7. Handheld measurements for soil temperatures at the Barney farm (Delamere soil series sampling transect) at the 0.5 cm (A), 2 cm (B), 5 cm(C), and 12 cm (D) soil depths during 2015. Shaded areas indicate periods of no significant differences among tillage practices.

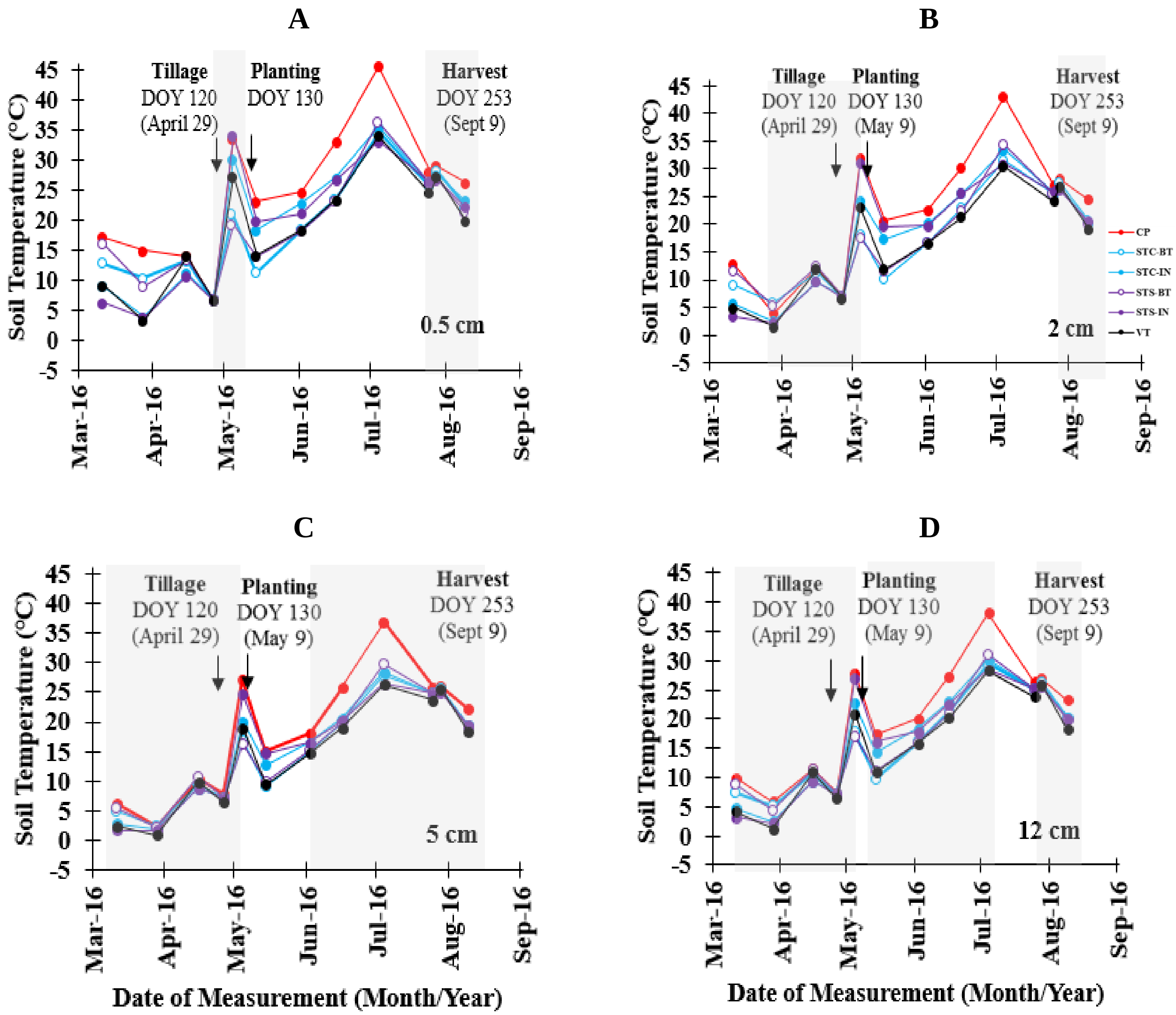

Figure 8. Handheld measurements for soil temperatures at the Barney farm (Delamere soil series sampling transect) at the 0.5 cm (A), 2 cm (B), 5 cm(C), and 12 cm (D) soil depths during 2016. Shaded areas indicate periods of no significant differences among tillage practices.

During 2015 and 2016, mean soil volumetric water content was observed to be significantly higher in VT, STC-BT, and STS-BT treatments when compared to CP, STC-IN, and STS-IN treatments across all measurements dates at all farms. During the growing season, there were few occurrences where soil θ was significantly different in one treatment over all others (Table 6). When tillage effects were evident, the CP mean soil θ was numerically the lowest among all other treatments, but not significantly different from STC-IN and STS-IN

Table 6. Summary of mean soil volumetric water content for dates that handheld measurements were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT)]at the Barney, Fergus Falls, and Mooreton farms in 2015 and 2016.

Farm	Date	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	-----------------------------------		θ	----------------------------------		
Barney	4/23/2015	0 - 5	0.10b†	0.23a	0.15b	0.19a	0.15b	0.20a
	6/03/2015	0 - 5	0.19b	0.37a	0.21b	0.31a	0.23b	0.32a
	9/25/2015	0 - 5	0.19b	0.29a	0.20b	0.23ab	0.19b	0.25ab
	4/26/2016	0 - 5	0.39b	0.42a	0.36b	0.43a	0.42b	0.45a
	5/04/2016	0 - 5	0.26b	0.34a	0.28b	0.38a	0.31ab	0.36a
	5/14/2016	0 - 5	0.22b	0.27a	0.25b	0.30a	0.26ab	0.28a
	6/16/2016	0 - 5	0.19b	0.40a	0.32a	0.39a	0.31a	0.28a
	7/04/2016	0 - 5	0.26b	0.34a	0.24b	0.33a	0.21b	0.30a
	7/25/2016	0 - 5	0.20b	0.27a	0.18b	0.25a	0.18b	0.24a
Fergus Falls	4/27/2015	0 - 5	0.13b	0.29a	0.13b	0.15b	0.13b	0.16b
	6/10/2015	0 - 5	0.20b	0.31a	0.23b	0.29a	0.23b	0.32a
	7/21/2015	0 - 5	0.23b	0.35a	0.25b	0.33a	0.23b	0.32a
	8/27/2015	0 - 5	0.16b	0.37a	0.18b	0.21b	0.18b	0.32a
	9/25/2015	0 - 5	0.20b	0.32a	0.21ab	0.30ab	0.21ab	0.26ab
	4/04/2016	0 - 5	0.19b	0.26a	0.30a	0.31a	0.25ab	0.27a
	4/16/2016	0 - 5	0.18b	0.22b	0.27a	0.34a	0.26a	0.32a
	4/23/2016	0 - 5	0.14b	0.27a	0.28a	0.34a	0.25ab	0.36a
	5/05/2016	0 - 5	0.14b	0.20b	0.26a	0.29a	0.28a	0.30a
	5/16/2016	0 - 5	0.20b	0.37a	0.24b	0.32a	0.25b	0.39a
	6/05/2016	0 - 5	0.23b	0.39a	0.25b	0.36a	0.25b	0.38a
	7/02/2016	0 - 5	0.15b	0.21ab	0.19b	0.26a	0.21ab	0.26a
	7/21/2016	0 - 5	0.30b	0.46a	0.36ab	0.44a	0.39ab	0.43a
	9/07/2016	0 - 5	0.28b	0.34a	0.34a	0.38a	0.34a	0.37a
Mooreton	4/28/2016	0 - 5	0.26b	0.29a	0.27ab	0.34a	0.29ab	0.33a
	5/04/2016	0 - 5	0.19ab	0.21a	0.14b	0.21a	0.15b	0.22a
	5/11/2016	0 - 5	0.13b	0.25a	0.18b	0.24a	0.13b	0.26a
	6/01/2016	0 - 5	0.21b	0.17b	0.21b	0.30a	0.20b	0.29a
	6/16/2016	0 - 5	0.11b	0.21ab	0.19b	0.31a	0.20ab	0.26a
	7/22/2016	0 - 5	0.13b	0.18a	0.17ab	0.20a	0.14b	0.18a
	7/29/2016	0 - 5	0.19b	0.24a	0.21b	0.33a	0.25b	0.31a
	8/10/2016	0 - 5	0.28b	0.36a	0.39a	0.35a	0.40a	0.41a

†Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

tillage treatment (Figure 9). In general, tillage practices did not significantly differ and affect soil volumetric water contents in the late season growing season and prior to harvest.

Near Continuous Measurements

In 2016, a three-way interaction of tillage, date, and depth was never observed to be significant for daily mean, maximum, or minimum soil T during any month in any of the Fergus Falls and Mooreton farms. Instead, a significant tillage by depth interaction was nearly always evident within each month individually (Table 7; Tables A2, A3, A4, A5, and A6; Figures 10, 11, 12, and 13). When significant differences occurred, tillage practices affected daily mean soil T at the 5, 10, 25, and 40 cm soil depths during 6, 3, 1, and 4 months of measurements, respectively, across the Barney and Mooreton farms. However, these significant differences in daily mean soil T varied from less than 1 to 2°C. Similar to results for handheld soil temperature measurements, few or no differences were observed between daily mean soil T in CP, STC-IN, and STS-IN zones and between mean soil T in the VT, STC-BT and STS-BT zones for the Barney and Mooreton farms and all soil depths. Near planting, during the growing season, and near harvest, daily mean soil T at all depths generally varied by 1°C or less (Figure 10, 11, 12, and 13). In 2016, the three-way interaction of tillage, date, and depth was never observed to be significant for daily mean soil θ during any month in any of the Fergus Falls and Mooreton farms. Instead, a significant tillage by depth interaction was nearly always evident within each month individually (Table 8; Tables A2, A3, A4, A5, and A6; Figures 14, 15, 16, and 17).

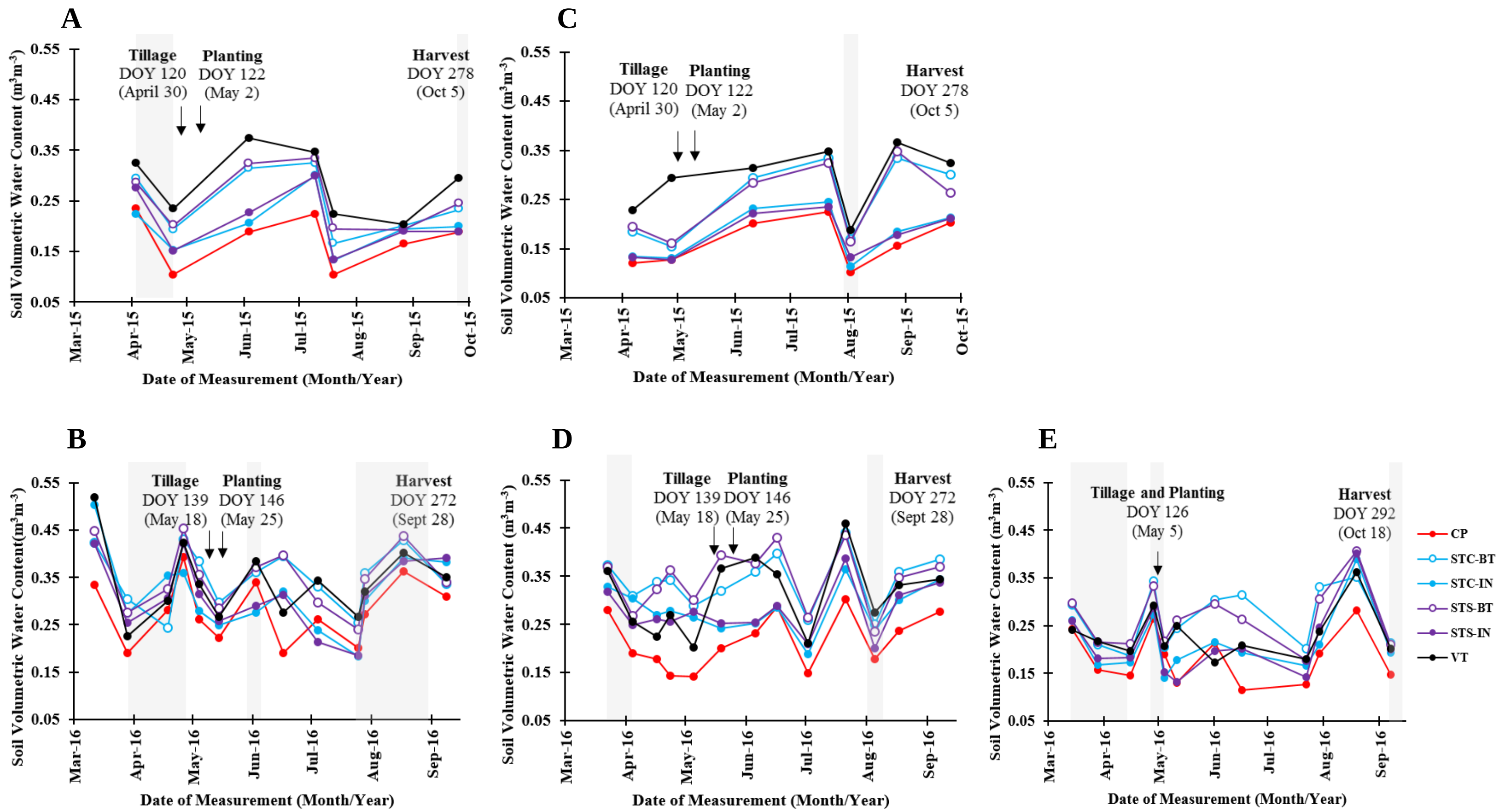

Figure 9. Handheld measurements for soil volumetric water content at 0-5 cm depth at the Barney farm Delamere soil series sampling transect in 2015 (A) and 2016 (B), Fergus Falls farm Lakepark soil series sampling transect in 2015 (C) and 2016 (D) and Mooreton farm Fargo Clay-NE soil series sampling transect in 2016 (E). Shaded areas indicate periods of no significant differences among tillage practices.

Significant differences were concentrated at or in the thawing period prior to spring tillage and in the late growing season. Where significant differences were evident, soil θ varied from 0.02 to 0.14 $m^3 m^{-3}$. During the growing season, there were no occurrences where soil θ was significantly different in one treatment over all others and at all depths. Significant differences in soil θ were primarily observed at the 40 cm soil depth for the Mooreton farm and were concentrated within growing season. At the Barney farm, significant differences occurred in January and February (i.e., soils were frozen) at nearly all depths and during the growing season, near the soil surface (5 cm soil depth).

Table 7. Summary of the daily mean soil temperature for near continuous measurements for soil series and depths that were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT) and depth interactions].

Farm	Time	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	-----------------	-----------------	-----------------	°C	-----------------	-----------------
Barney	Nov 2015	5	11.58ab†	12.65a	11.44b	11.24b	11.60ab	11.38b
		10	12.24ab	12.76a	11.76ab	11.58b	11.72ab	11.96ab
		40	14.41a	12.68b	13.85ab	13.93ab	13.93ab	14.28a
	Dec 2015	5	9.82b	10.81a	10.29ab	10.25ab	10.13ab	9.96b
		10	10.36ab	10.92a	10.40ab	10.45ab	10.07b	10.40ab
		40	11.90a	10.91b	11.72ab	11.81a	11.62ab	11.95a
	Jan 2016	5	6.90b	9.03a	9.67a	9.73a	8.94a	8.12ab
		10	7.54b	9.13ab	9.79a	9.91a	8.90ab	8.86ab
	May 2016	5	28.33a	26.54b	27.97a	27.51ab	28.68a	28.33a
		40	25.34ab	26.22ab	25.68ab	25.25b	26.55a	25.51ab
	June 2016	5	32.34a	30.56b	31.88a	31.71ab	32.68a	32.08a
		40	29.63ab	30.46a	29.87ab	29.33ab	30.49a	29.45b
	Oct 2016	5	20.91ab	21.32a	20.80ab	20.36b	20.75ab	20.94ab
Mooreton	Sept 2016	25	33.02a	NA‡	32.32b	32.37b	32.40b	32.29b

†Different letters within a row are significantly different at the 0.05 level using Tukey’s HSD test.
‡ NA-Not Available due to dysfunctional datalogger

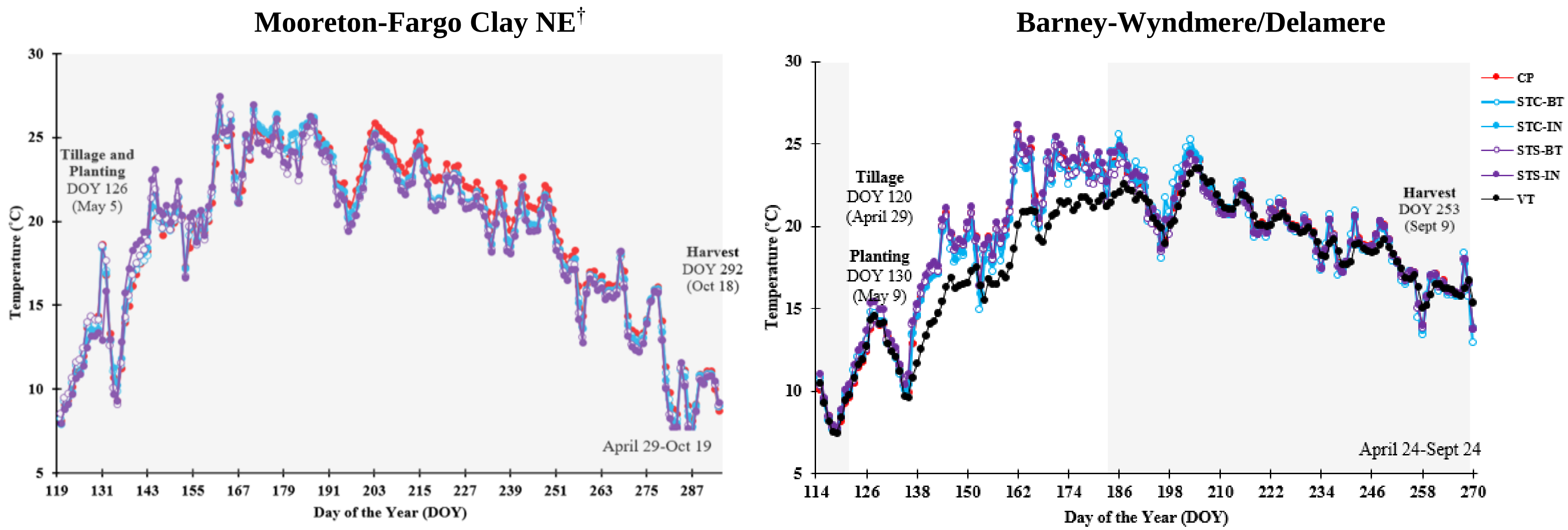

Figure 10. Near continuous measurements for soil temperature from April 29-October 19 at the Mooreton farm and from April 24-September 24 at the Barney farm at the 5 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the analysis of the Mooreton farm due to dysfunctional datalogger.

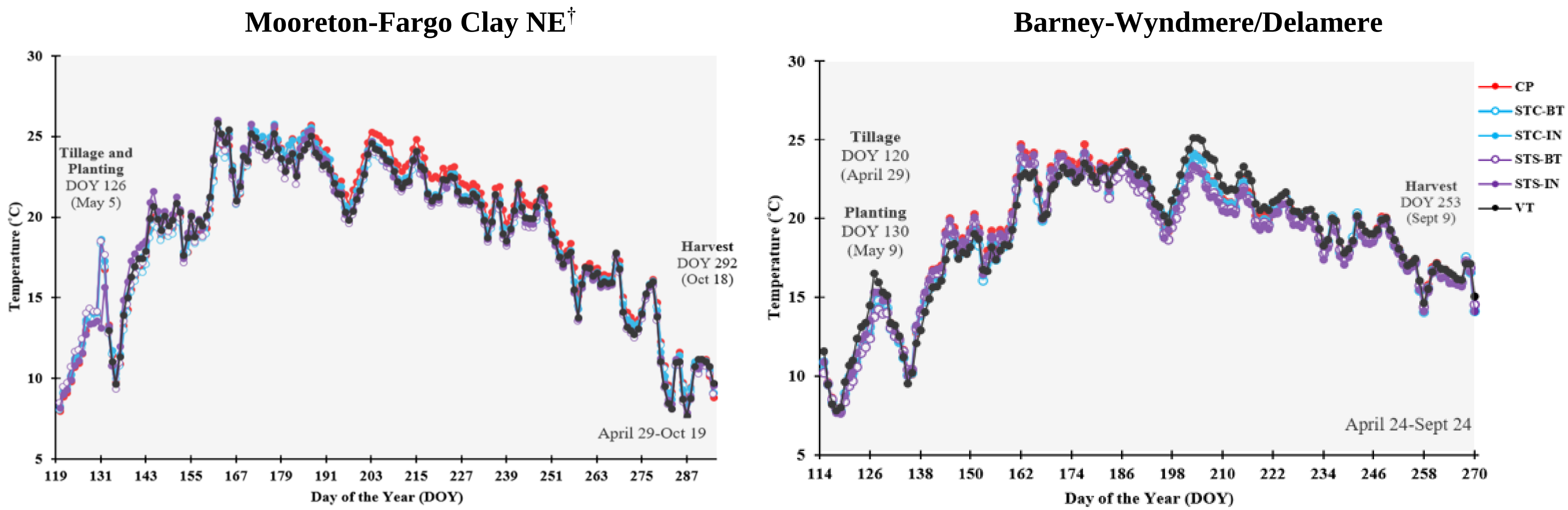

Figure 11. Near continuous measurements for soil temperature from April 29-October 19 at the Mooreton farm and from April 24-September 24 at the Barney farm at the 10 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the early analysis of the Mooreton farm due to dysfunctional datalogger.

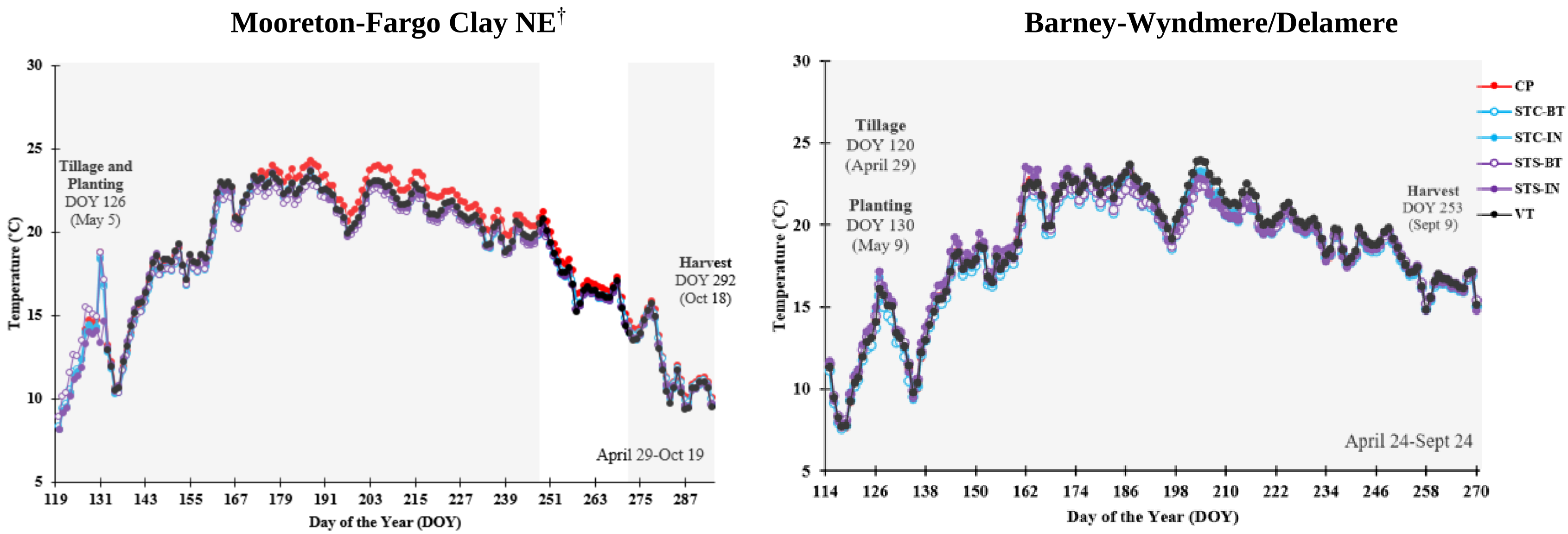

Figure 12. Near continuous measurements for soil temperature from April 29-October 19 at the Mooreton farm and from April 24-September 24 at the Barney farm at the 25 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the early analysis of the Mooreton farm due to dysfunctional datalogger.

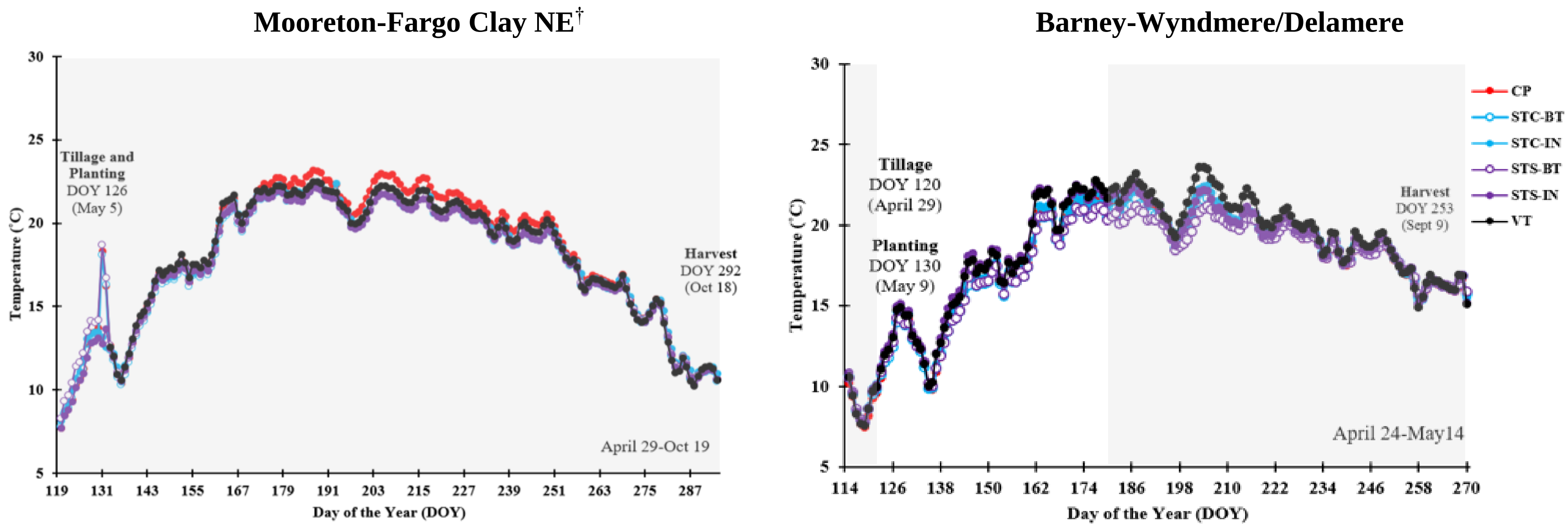

Figure 13. Near continuous measurements for soil temperature from April 29-October 19 at the Mooreton farm and from April 24-September 24 at the Barney farm at the 40 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the early analysis of the Mooreton farm due to dysfunctional datalogger.

Table 8. Summary of the mean volumetric water contents for near continuous measurements as significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT) and depth interactions] at Barney and Mooreton farms in 2016.

Farm	Time	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	-----------------------------------			θ-----------------------------------		
Barney	Jan 2016	5	0.06b†	0.09a	0.07b	0.10a	0.09b	0.08a
		10	0.07b	0.08b	0.13a	0.09a	0.098a	0.06b
		25	0.09b	0.10ab	0.13ab	0.14a	0.12ab	0.10ab
		40	0.09b	0.08b	0.16a	0.14a	0.10ab	0.11ab
	Feb 2016	10	0.08b	0.09ab	0.16a	0.01ab	0.14ab	0.09ab
		40	0.08b	0.08b	0.17a	0.13a	0.12ab	0.12ab
	May 2016	5	0.14ab	0.20a	0.18ab	0.12b	0.18ab	0.18ab
	June 2016	5	0.13ab	0.19a	0.16ab	0.12b	0.17ab	0.15ab
	July 2016	5	0.12ab	0.20a	0.16ab	0.09b	0.14ab	0.16ab
Mooreton	May 2016	40	0.36ab	NA‡	0.24b	0.33ab	0.38a	0.28ab
	June 2016	5	0.31a	NA	0.19b	0.21ab	0.20ab	0.26ab
		40	0.37a	NA	0.25b	0.33ab	0.40a	0.33ab
	July 2016	40	0.38a	NA	0.26b	0.32ab	0.41a	0.35ab
	Aug 2016	40	0.38a	NA	0.25b	0.34ab	0.43a	0.37ab

†Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

‡ NA-Not Available due to dysfunctional datalogger

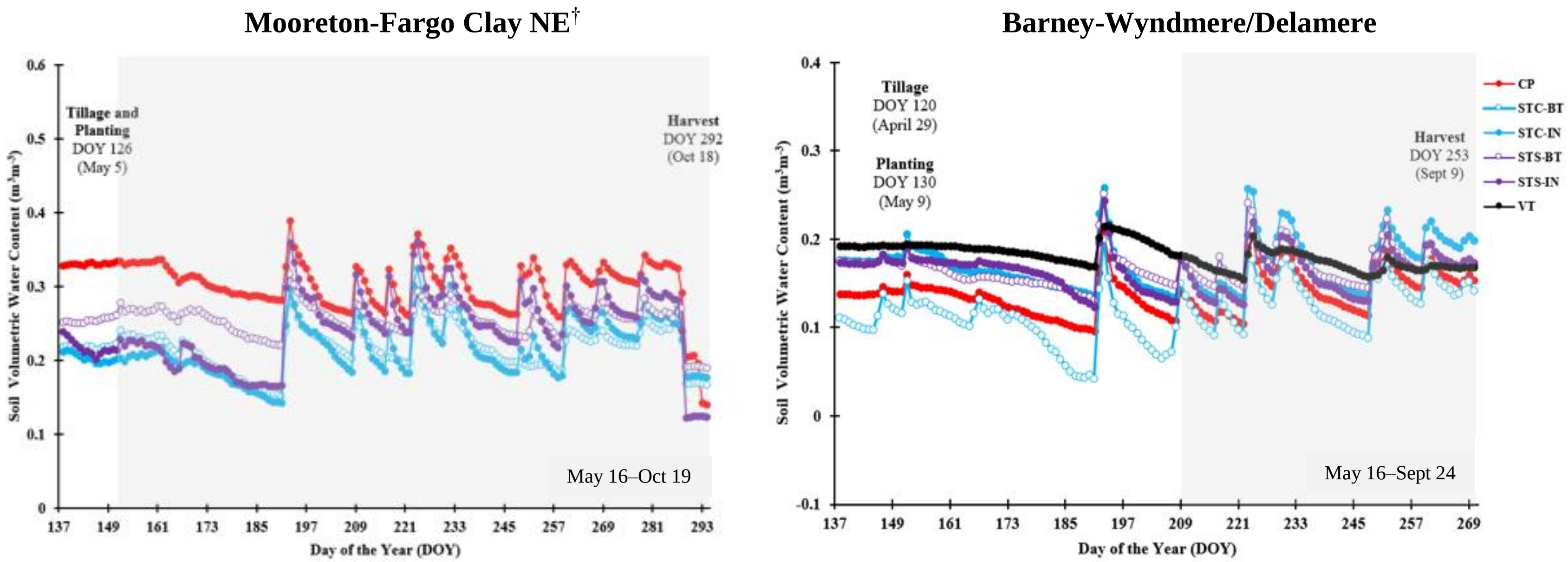

Figure 14. Near continuous measurements for soil volumetric water content from May 16-October 19 at the Mooreton farm and from May 16-September 24 at the Barney farm at the 5 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the analysis of the Mooreton farm due to dysfunctional datalogger.

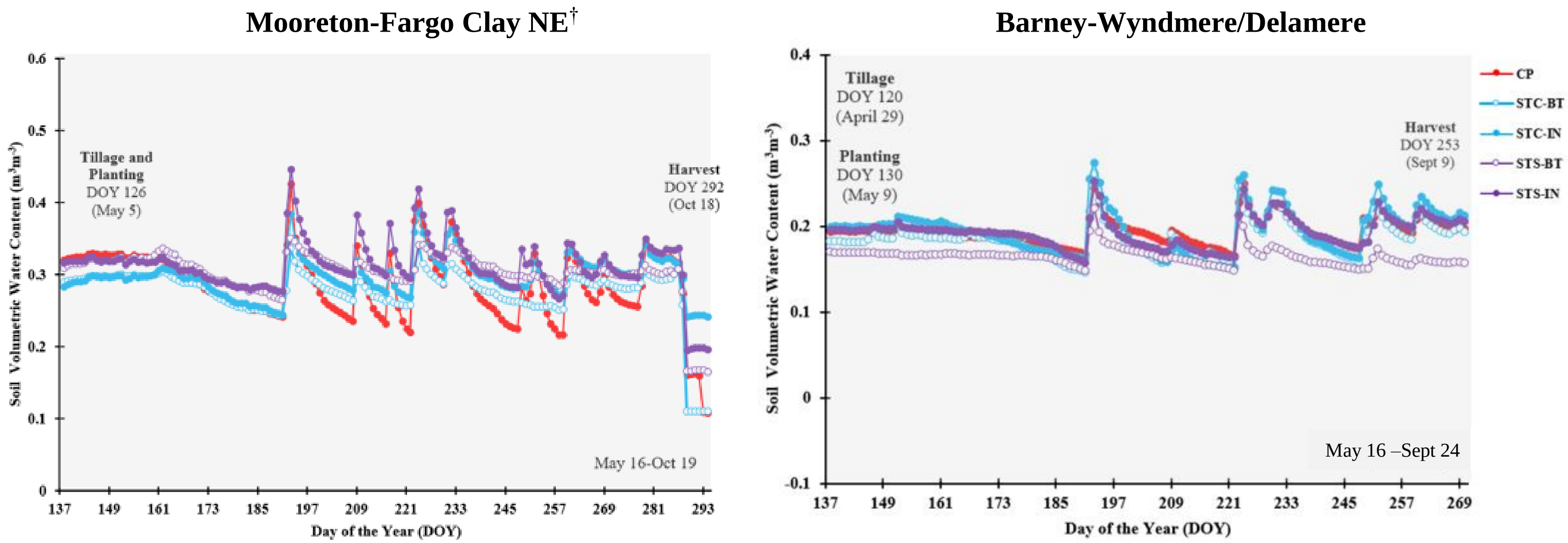

Figure 15. Near continuous measurements for soil volumetric water content from May 16-October 19 at the Mooreton and from May 16-September 24 at the Barney farm at the 10 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the analysis of the Mooreton and Barney farms due to dysfunctional datalogger.

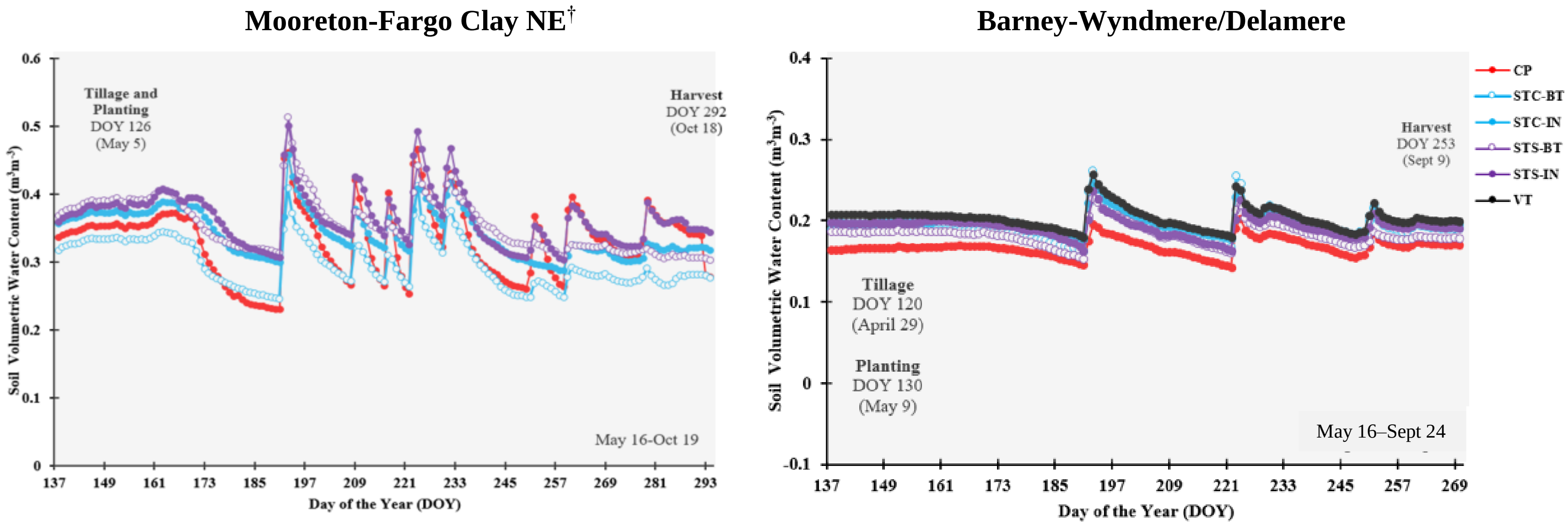

Figure 16. Near continuous measurements for soil volumetric water content from May 16-October 19 at the Mooreton farm and from May 16-September 24 at the Barney farm at the 25 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

† Vertical tillage was not included in the analysis of the Mooreton farm due to dysfunctional datalogger.

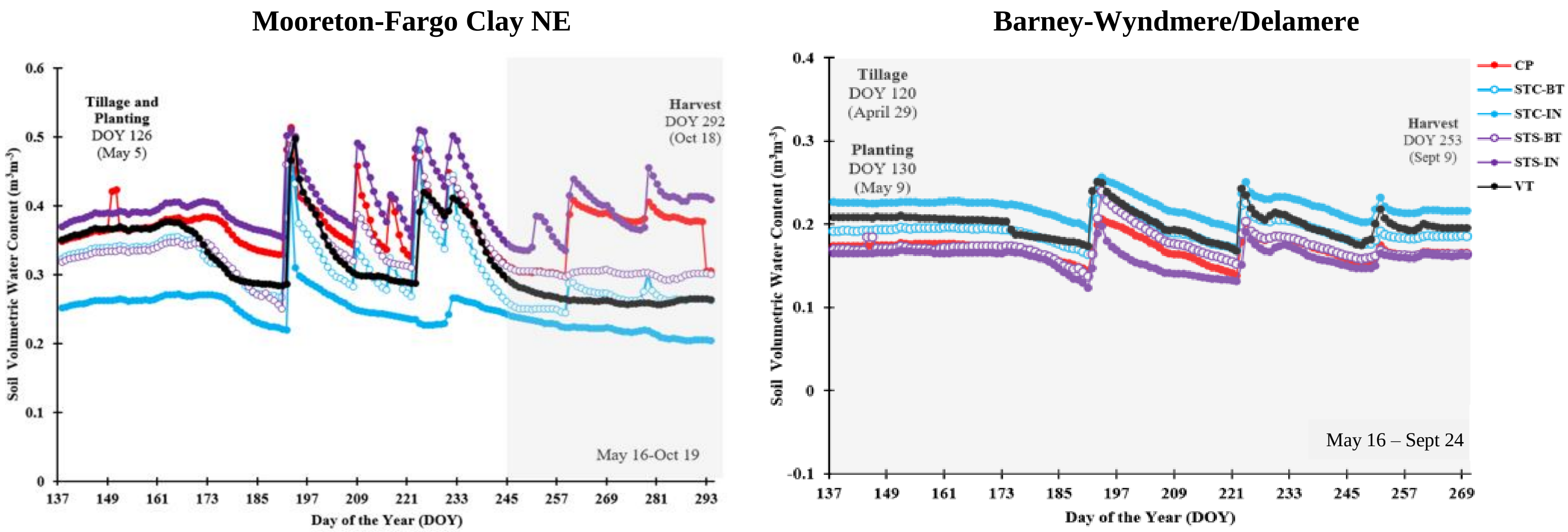

Figure 17. Near continuous measurements for soil volumetric water content from April 29-October 19 at the Mooreton farm and from May 16-September 24 at the Barney farm at the 40 cm soil depth in 2016. Shaded areas indicate periods of no significant differences among tillage practices.

Soil Penetration Resistance

Mean soil penetration resistance across all farms, soil series, and depths ranged from 62 to 2930 kPa in 2016 (Figure 18). In general, higher soil penetration resistance was observed in the first measurements (May) across all farms and respective transects. Soil penetration resistance decreased through the growing season (July) and near harvest (September) is observed to be the lowest at all farms and their respective transects.

A significant tillage by depth interaction in penetration resistance was observed at the Barney farm in both the Wyndmere and Delamere soil series sampling transects and at the Fergus Falls farm in both the Barnes and Lakepark soil series sampling transects (Table 9). At the Barney and Fergus Falls farms in the upper soil profile (0 to 20 cm), the mean penetration resistance was generally the least in CP, STC-IN, and STS-IN zones and were significantly different from STC-BT, STS-BT, and VT tillage treatments (Table 10). At the Mooreton farm, at both nonsaline soil series sampling transects (i.e., NE and SE quadrants), no significant differences were observed in penetration resistance based on tillage treatment. There were no significant difference in soil penetration resistance observed in the lower soil profiles (21 to 45 cm) at the Barney, Fergus Falls, and Mooreton farm for all soil series sampling transects.

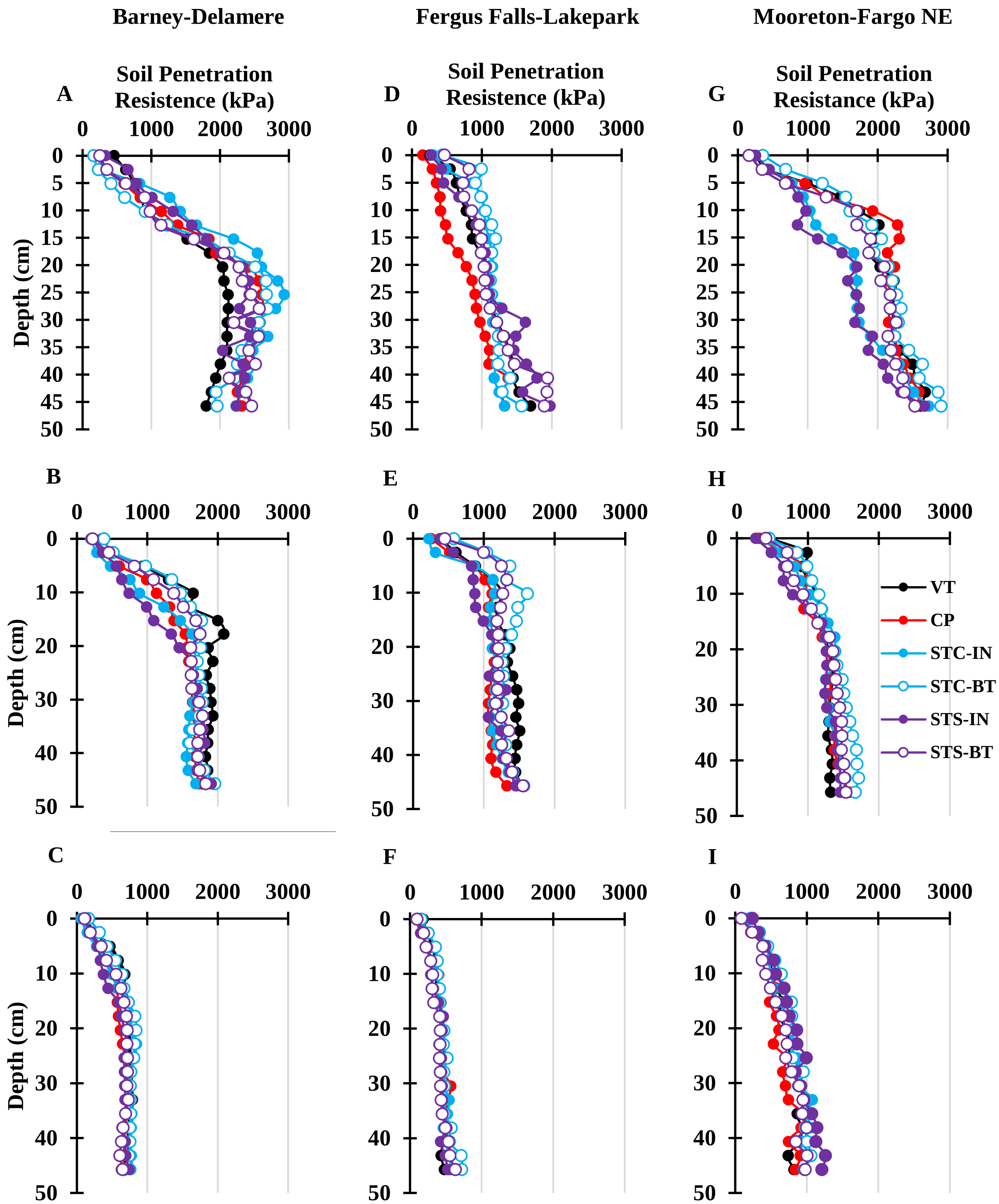

Figure 18. Penetration resistance for the soil profile at the Barney farm, Delamere soil series sampling transect, Fergus Falls farm on May 16th (A), July 16th (B), and September 16th (C), Lakepark soil series sampling transect on May 16th (D), July 16th (E), and September 16th (F), and Mooreton farm, NE soil series sampling transect on May 16th (G), July 16th (H), and September 16th (I) in 2016.

Table 9. Analysis of variance P-value table for the soil penetration resistance analyzed for fixed effects of Date, Tillage, Depth, and their interactions. The analysis were for the Wyndmere and Delamere soil series sampling transect at the Barney farm, Barnes and Lakepark soil series sampling transect at the Fergus Falls farm, and in the NE soil series sampling transect at the Mooreton farm. Data were collected near planting (May 16th), during rapid growth (July 16th), and near harvesting (September 16th) in 2016.

Farm	Soil Transect	Source	P-value
Barney	Wyndmere	Date	<0.0001
		Tillage	<0.0001
		Depth	<0.0001
		Tillage*Depth	<0.01
		Date*Tillage	<0.001
		Date*Depth	<0.01
		Date*Tillage*Depth	1.00
	Delamere	Date	<0.0001
		Tillage	<0.0001
		Depth	<0.0001
		Tillage*Depth	<0.05
		Date*Tillage	<0.0001
		Date*Depth	<0.0001
		Date*Tillage*Depth	0.83
Fergus Falls	Barnes	Date	<0.0001
		Tillage	<0.0001
		Depth	<0.0001
		Tillage*Depth	<0.001
		Date*Tillage	<0.0001
		Date*Depth	<0.05
		Date*Tillage*Depth	0.31
	Lakepark	Date	<0.0001
		Tillage	<0.0001
		Depth	<0.0001
		Tillage*Depth	<0.0001
		Date*Tillage	<0.0001
		Date*Depth	<0.0001
		Date*Tillage*Depth	0.90
Mooreton[†]	Fargo	Date	<0.0001
		Tillage	<0.0001
		Depth	<0.0001
		Tillage*Depth	0.99
		Date*Tillage	<0.0001
		Date*Depth	<0.0001
		Date*Tillage*Depth	0.92

[†]Values at the Mooreton farm are for 2016 only and in the subsurface drained, non-saline soil (i.e. NE quadrant).

Table 10. Summary of the mean soil penetration resistance for soil series and depths that were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT) and depth interactions].

Farm	Transect	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	---------------------------------kPa---------------------------------					
Barney	Wyndmere	10	131.8a†	154.9a	95.5b	147.9a	77.6b	125.9ab
		12	151.4a	190.5a	134.9ab	166a	81.3b	162.2a
		15	173.8ab	213.8a	173.8a	182a	102.3b	195a
	Delamere	0	17.8b	32.4a	18.6b	27.5a	28.2ab	24.5ab
		2.5	39.8ab	61.7ab	29.5a	46.8b	50.1ab	41.7a
Fergus Falls	Barnes	0	18.2b	33.1a	22.4ab	35.5a	33.1a	28.8ab
		2.5	38ab	55ab	34.7b	66.1a	40.7ab	55ab
		5	57.5b	85.1b	81.3ab	102.3a	67.6b	83.2ab
	Lakepark	0	25.1b	35.5a	23.4ab	38a	22.4b	42.7a
		2.5	39.8b	69.2a	39.8b	83.2a	38b	79.4a
		5	51.3b	89.1a	75.9ab	112.2a	56.2b	89.1a
		7.5	60.3b	97.7b	100ab	125.9a	75.9b	100ab

†Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test

Soil Chemical Properties

Few significant differences (P≤0.05) among tillage practices were observed for soil chemical properties among the three farms (Table 11). Of the total 120 possible soil-depth main effects (15 chemical properties multiplied by eight sampling transect = 120 potential effects), we observed 88 significant soil-depth main effects. However, we observed only 21 significant tillage main effects and 2 significant tillage-by-depth interactions out of the total 240 possible effects interactions among the eight sampling transects at the three farms. Summary of significant differences among reduced tillage practices for soil chemical properties with either a tillage main effect or a tillage-by-depth interaction at their respective sampling transect are displayed in Table 12.

Table 11. Analysis of variance P-value table for soil chemical properties (n=15) analyzed for fixed effects of tillage, depth, and tillage-by-depth interactions for eight sampling transects across three farms.

Source	Chemical Property	Wyndmere	Delamere	Barnes	Lakepark	Fargo-NE	Fargo-SE	Fargo-NW	Fargo-SW
		------Barney farm------		-Fergus Falls farm-		---------------Mooreton farm---------------			
Tillage	NO_3-N	0.09	<0.05	<0.05	<0.05	0.08	0.11	<0.0001	0.14
	NH_4-N	0.08	<0.05	<0.05	0.11	0.62	0.06	<0.01	0.26
	P	0.13	<0.01	0.29	0.46	<0.05	0.40	<0.01	0.06
	K	0.39	0.40	0.72	0.71	0.68	0.60	<0.05	0.56
	S	0.72	0.21	0.44	0.44	0.49	0.07	0.76	0.10
	Zn	1.00	0.95	0.27	0.60	0.72	0.20	0.73	<0.01
	Fe	1.00	0.17	0.80	0.46	0.27	<0.05	<0.05	0.99
	Mn	0.93	0.47	0.72	0.13	0.94	0.14	0.11	0.78
	Cu	0.43	0.41	0.87	0.87	0.35	0.27	<0.05	0.81
	Ca	0.97	0.94	0.15	0.46	0.19	0.30	0.96	0.38
	Mg	0.84	0.09	0.99	0.06	0.33	<0.01	<0.05	0.39
	Na	0.96	0.22	0.56	0.73	<0.05	0.41	0.52	<0.05
	TC	0.96	0.36	0.19	0.73	0.05	0.45	0.07	0.32
	IC	0.98	0.94	0.29	0.71	0.40	0.45	0.13	0.53
	OC	0.92	0.31	0.14	0.99	0.06	0.58	0.06	0.22
Depth	NO_3-N	0.30	0.08	<0.01	<0.0001	<0.05	0.62	0.70	0.81
	NH_4-N	<0.05	<0.01	<0.0001	<0.0001	0.55	<0.05	0.51	0.35
	P	<0.0001	<0.001	<0.01	0.24	0.001	0.28	<0.01	<0.001
	K	<0.0001	<0.0001	<0.0001	<0.001	<0.01	<0.0001	<0.05	<0.0001
	S	<0.05	<0.001	0.35	0.32	0.46	<0.05	<0.0001	<0.001
	Zn	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Fe	<0.001	0.27	<0.001	<0.0001	<0.0001	<0.0001	<0.0001	<0.01
	Mn	<0.01	0.28	<0.0001	<0.001	<0.05	0.12	<0.001	<0.05
	Cu	0.70	0.31	0.62	<0.0001	0.06	<0.0001	0.83	<0.05
	Ca	<0.05	0.26	0.36	<0.0001	<0.05	0.32	<0.001	<0.05
	Mg	0.61	0.76	<0.05	<0.05	<0.01	<0.01	<0.0001	<0.0001
	Na	0.12	<0.01	0.30	<0.01	<0.05	<0.05	<0.0001	<0.01
	TC	<0.05	<0.01	0.17	<0.01	<0.0001	<0.05	<0.0001	<0.001
	IC	<0.05	<0.01	<0.05	<0.0001	0.23	0.58	0.22	<0.001
	OC	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.05	<0.0001	<0.0001
Tillage × Depth	NO_3-N	0.39	0.15	0.69	0.56	0.87	0.40	0.97	0.90
	NH_4-N	0.26	0.97	<0.05	0.23	0.86	0.39	0.44	0.74
	P	0.45	0.07	0.58	0.46	0.31	0.39	0.74	0.59
	K	1.00	0.99	0.99	0.61	0.93	0.38	0.51	0.49
	S	0.88	0.48	0.45	0.44	0.15	0.77	0.18	0.91
	Zn	1.00	0.98	0.52	0.64	0.83	0.90	0.80	<0.05
	Fe	1.00	0.88	0.98	0.30	0.57	0.42	0.63	1.00
	Mn	1.00	0.96	0.60	0.44	1.00	0.56	0.76	0.96
	Cu	0.43	0.44	0.96	0.83	1.00	0.81	0.80	1.00
	Ca	0.99	0.97	0.77	0.99	0.98	0.71	0.48	0.98
	Mg	0.97	0.40	0.92	0.06	0.91	0.93	0.87	0.62
	Na	1.00	0.97	0.91	0.39	0.63	0.75	0.98	0.96
	TC	0.98	0.95	0.97	0.39	0.65	0.82	0.82	0.11
	IC	0.99	0.98	1.00	0.71	0.55	0.52	0.50	0.89
	OC	0.90	0.62	0.98	0.89	0.80	0.82	0.80	0.33

Table 12. Summary of mean soil chemical properties as significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT)].

Farm	Transect	Parameter	Depth†	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
Barney	Delamere	NO_3-N (mg kg^{-1})	0-30	24.2ab‡	39.9a	14.7b	12.0b	15.97ab	17.47ab
		NH_4-N (mg kg^{-1})	0-30	4.87ab	3.05b	4.63ab	5.09a	3.73ab	3.52ab
		P (mg kg^{-1})	0-30	8.7b	10.3ab	4.7b	7.4b	8.9ab	22.1a
Fergus Falls	Barnes	NO_3-N (mg kg^{-1})	0-30	7.60ab	9.55a	7.23ab	5.25b	8.53ab	6.86ab
		NH_4-N (mg kg^{-1})	0-15	3.41ab	4.12ab	4.13a	3.23b	3.12b	3.67ab
	Lakepark	NO_3-N (mg kg^{-1})	0-30	8.28a	8.59a	7.20ab	5.42b	7.73ab	7.25ab
Mooreton	Fargo - NE	P (mg kg^{-1})	0-30	10.5ab	11.8ab	15.8a	8.7ab	14.9ab	8.3b
		Na (mg kg^{-1})	0-30	39.6a	30.9ab	22.8ab	21.0b	21.7ab	22.1ab
	Fargo - SE	Fe (mg kg^{-1})	0-30	44.3ab	45.6ab	48.1a	50.6a	40.5ab	36.1b
		Mg (mg kg^{-1})	0-30	1519b	1769ab	1684ab	1662ab	1915a	1891a
	Fargo - NW	NO_3-N (mg kg^{-1})	0-30	15.73a	16.39a	26.8a	13.4b	6.70b	5.27b
		NH_4-N (mg kg^{-1})	0-30	20.48a	18.23ab	15.70ab	8.06ab	5.39b	5.67b
		P (mg kg^{-1})	0-30	14.6ab	12.2b	21.6a	15.3ab	15.7ab	11.3b
		K (mg kg^{-1})	0-30	268a	265ab	225ab	241ab	220b	225ab
		Fe (mg kg^{-1})	0-30	45.9a	49.1ab	37.5b	37.7ab	42.2ab	46.3ab
		Cu (mg kg^{-1})	0-30	1.83a	1.79ab	1.76ab	1.68ab	1.61b	1.65ab
		Mg (mg kg^{-1})	0-30	2746ab	2480ab	2887a	2851a	2389ab	2204b
	Fargo - SW	Zn (mg kg^{-1})	0-15	0.59b	0.59ab	0.74ab	0.56b	0.82a	0.55b
		Na (mg kg^{-1})	0-30	225.8a	285.72a	156.5b	163.0b	202.0a	189.06a

† Soil depths noted as 0-30cm are for significant tillage main effects (i.e., no significant tillage by depth interaction). Soil depths noted for 0-15 or 15-30cm are for significant tillage by depth interactions.

‡Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

At the Barney farm, no significant differences were observed among the reduced tillage practices in the Wyndmere soil series sampling transect for all soil chemical properties. In the Delamere soil series sampling transect, soil NO_3-N concentrations averaged across the two soil depths were significantly higher in the VT treatment as compared to both STC-IN and STC-BT zones (i.e., 39.9 vs. 14.7 and 12 mg kg^{-1}, respectively). Additionally, soil-test P concentrations averaged across the two soil depths in the Delamere soil series were significantly higher in the STS-BT zone as compared to the CP treatment (i.e., 22.1 vs. 8.7 mg kg^{-1}, respectively) and (Table 12). The mixed model showed significant NH_4-N concentrations differences among tillage practices in the Delamere soil series; however, this effect was not confirmed with the posthoc Tukeys' mean separation.

At the Fergus Falls farm, both Barnes and Lakepark soil series sampling transects had significant differences in soil NO_3-N concentrations among the reduced tillage practices. Soil NO_3-N concentrations when averaged across the two soil depths in the Barnes soil series were significantly higher in the VT treatment as compared to the STC-BT zone (i.e., 9.55 vs. 5.25 mg kg^{-1}, respectively). Similarly, soil NO_3-N concentrations when averaged across the two soil depths in the Lakepark soil series sampling transect were significantly higher in both the CP and VT as compared to the STC-BT zone (i.e., 8.28 and 8.59 vs. 5.42 mg kg^{-1}, respectively). Soil NH_4-N concentrations in the 0-15 cm soil depth in the Barnes soil series sampling transect were significantly higher in the STC-IN zone as compared to the STC-BT and STS-IN zones (i.e., 4.13 vs. 3.23 and 3.12 mg kg^{-1}, respectively). Soil NO_3-N concentrations for both soil series at the Fergus Falls farm were the lowest among eight sampling transects at the three farms.

At the Mooreton farm, the Fargo-NW soil series sampling transect had a significant difference in soil NO_3-N and NH_4-N concentrations among reduced tillage practices. When averaged across two soil depths, NO_3-N concentrations were significantly higher in CP, VT, and STC-IN zone as compared to the STC-BT, STS-IN, and STS-BT zone (i.e., 15.73, 16.39, and 26.8 vs. 13.4, 6.70, and 5.27 mg kg^{-1}, respectively). Soil NH_4-N concentrations were significantly higher in CP as compared to the STS-IN and STS-BT zones (i.e., 20.48 vs. 5.39 and 5.67 mg kg^{-1}, respectively). Both the Fargo-NE and Fargo-NW soil series sampling transects had significant differences among the soil-test P concentrations. When averaged across the two soil depths the Fargo-NE soil series sampling transect showed significant differences among the STC-IN and STS-BT zones (i.e., 15.8 vs. 8.3 mg kg^{-1}, respectively). At the Fargo-NW soil series sampling transect, soil-test P concentrations were significantly higher in the STC-BT zone as compared to VT and the STS-BT zone (i.e., 21.6 vs. 12.2 and 11.3 mg kg^{-1}, respectively). Soil-test P concentrations under VT tillage practices were slightly lower than STC-IN and STS-IN practices at the Mooreton farm at the NE and NW transects.

Plant Populations, Plant Heights, and Crop Yields

Plant populations and height measured in June 2015 and 2016 was not affected by tillage practice at any of the three farms (Table 13). Few significant differences in crop yields were observed among tillage practices at the three farms; however, ST treatments generally demonstrates higher crop yields. In 2015, VT corn yielded significantly higher than STS (i.e., 13497 vs. 12361 kg ha^{-1}, respectively) with no difference among the other tillage practices. In contrast, corn yields were not significantly affected by tillage at the Barney farm in 2015 (Figure 19). In 2016, soybean yields at both the Barney and Fergus Falls farms did not differ among tillage practices (Figure 20). At the Mooreton farm in 2016, corn yields were numerically greater in the nonsaline soils in the NE and SE soil series sampling transects when compared to saline soils in the NW and SW soil series sampling transects. In the saline soils, there were no significant differences in corn yield among tillage practices. In the nonsaline soils, ST practices yielded significantly higher than CP and VT practices. Likewise, corn yields were numerically greater in the surface-drained transects (SE and SW), when compared to the surface- and subsurface-drained transects (NE and NW). No significant differences were observed in corn plants heights under reduced tillage practices (Figure 21).

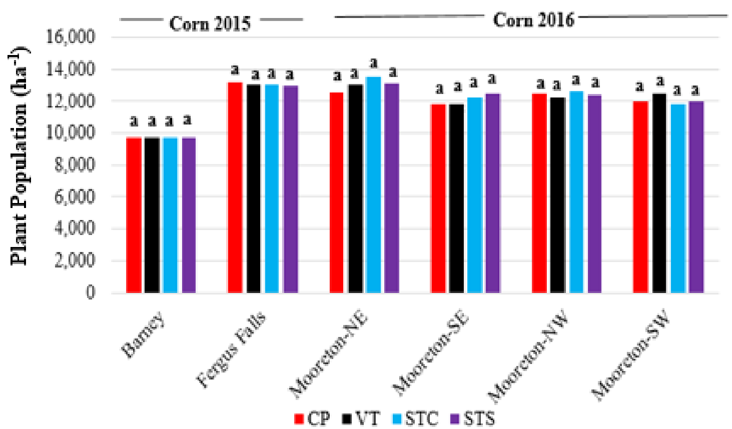

Figure 19. Corn crop yields under chisel plow (CP), vertical tillage (VT), strip tillage with coulter (STC), and strip tillage with shank (STS) in 2015 at the Barney, Fergus Falls, and Mooreton farms. Different letters among tillage practices at each farm are significantly different at the 0.05 level using Tukey's HSD test.

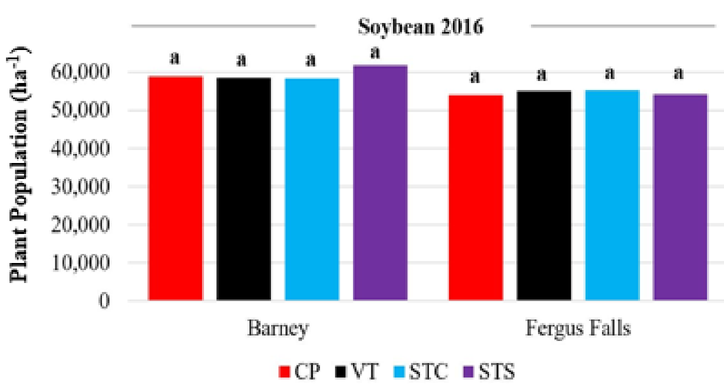

Figure 20. Soybean crop yields under chisel plow (CP), vertical tillage (VT), strip tillage with coulter (STC), and strip tillage with shank (STS) in 2015 at the Barney and Fergus Falls farms. Different letters among tillage practices at each farm are significantly different at the 0.05 level using Tukey's HSD test.

Table 13. Crop yields, plant populations, and plant heights under reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter (STC), and strip tillage with shank (STS)] at Mooreton, ND, Fergus Falls, MN and Barney, ND farms in 2015 and 2016.

Year	Farm	Crop Phase	Crop Yield and Plant Metrics	CP	VT	STC	STS
2015	Barney	Corn	Crop Yield (kg ha^{-1})	12737a†	12643a	12260a	12758a
			Plant Population (ha^{-1})	9,763a	9,763a	9,763a	9,763a
			Plant Height (cm)	20.32a	20.57a	19.56a	21.84a
	Fergus Falls	Corn	Crop Yield (kg ha^{-1})	13450ab	13497a	13410ab	12361b
			Plant Population (ha^{-1})	13,169a	13,018a	13,068a	12,933a
			Plant Height (cm)	19.56a	18.54a	20.83a	19.56a
	Mooreton	NA	Crop Yield (kg ha^{-1})	NA	NA	NA	NA
			Plant Population (ha^{-1})	NA	NA	NA	NA
			Plant Height (cm)	NA	NA	NA	NA
2016	Barney	Soybean	Crop Yield (kg ha^{-1})	3591a	3289a	3632a	3584a
			Plant Population (ha^{-1})	58,864a	58,564a	58,369a	61,698a
			Plant Height (cm)	NA	NA	NA	NA
	Fergus Falls	Soybean	Crop Yield (kg ha^{-1})	3268a	3484a	3275a	3336a
			Plant Population (ha^{-1})	54,056a	55,039a	55,235a	54,157a
			Plant Height (cm)	NA	NA	NA	NA
	Mooreton-NE	Corn	Crop Yield (kg ha^{-1})	13275c	12845d	14264a	13766b
			Plant Population (ha^{-1})	12,545a	13,018a	13,557a	13,152a
			Plant Height (cm)	30.48a	27.43a	27.18a	27.94a
	Mooreton-SE	Corn	Crop Yield (kg ha^{-1})	13827b	12388c	14809a	15165a
			Plant Population (ha^{-1})	11,837a	11,837a	12,275a	12,512a
			Plant Height (cm)	30.23a	28.96a	29.21a	30.23a
	Mooreton-NW	Corn	Crop Yield (kg ha^{-1})	12078a	11157a	13222a	11715a
			Plant Population (ha^{-1})	12,478a	12,242a	12,613a	12,411a
			Plant Height (cm)	27.18a	22.86a	27.43a	25.91a
	Mooreton-SW	Corn	Crop Yield (kg ha^{-1})	12630a	11769a	13457a	12401a
			Plant Population (ha^{-1})	12,006a	12,512a	11,837a	12,006a
			Plant Height (cm)	35.31a	33.53a	32.26a	31.50a

† Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

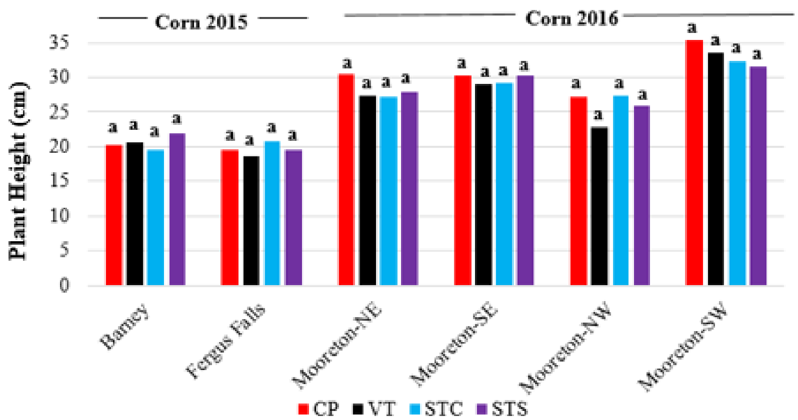

Figure 21. Corn plant heights under chisel plow (CP), vertical tillage (VT), strip tillage with coulter (STC), and strip tillage with shank (STS) in 2015 at the Barney, Fergus Falls, and Mooreton farms. Different letters among tillage practices at each farm are significantly different at the 0.05 level using Tukey's HSD test.

Discussion

Crop Residue Cover

The crop residue cover observed among tillage practices at the three farms used in this study are similar to those reported in the literature (Hussain et al., 1999; Raper et al., 1994; Vyn and Raimbault, 1992; NRCS, 1992). A significantly lower percentage of crop residue cover associate with the CP tillage practice was expected, and is a result of increased soil disturbance and incorporation of crop residue into the soil as compared to VT, STC, and STS tillage practices. The greater percentages of crop residue observed in all fields under the soybean crop phase is a result of a more thick and dense corn residue from the previous years' crop phase. At the Mooreton farm, subsurface drainage in the silty clay soils appeared to have an effect on our ability to detect significant differences in crop residue cover; significant differences were observed in surface- and subsurface-drained saline and nonsaline soils whereas no differences were observed in surface-drained saline and nonsaline soils. Although, not significant, the general trends among tillage practices and crop residue cover in the surface-drained soils were numerically similar to those in the surface- and subsurface-drained soils. This is possibly due to great spatial variability in the previous year's plant growth, and therefore variable crop residue distribution at the time of tillage, in these naturally drained silty clay soils. In the surface- and subsurface-drained saline soil (NW quadrant) at the Mooreton farm, STS was significantly lower than STC, similar to the finding of Vyn and Raimbault (1992). Although not significant, this general trend was also numerically observed among the other three quadrants at the Mooreton farm in 2016. This trend was not observed statistically or numerically at the Fergus Falls or Barney farms, which had higher crop residue cover and coarser soil textures. The differences observed between STC and STS at the Mooreton farm is likely associated with the timing of the tillage; STS performed in the fall and SPC performed in the spring. Griffith et al. (2009) examined the effect of the timing of primary tillage (fall vs. spring) and determined that delaying primary tillage until the spring resulted it greater residue coverage which could buffer erosion. The STS residue managers that sweep crop residue to the side of the tilled berm could have left crop residues loose and prone to movement during the fall and winter months prior to STC being performed. During the winter that bridged 2015 and 2016, little snow cover was observed throughout the region (NOAA, 2017b) which could have left loose crop residues prone to movement by the strong Northern Plain's winds.

Soil Temperatures and Soil Volumetric Water Contents

In the spring months during soil warming, soil T and θ are generally known to have a direct relationship. Vyn and Raimbault (1993) indicated that higher soil θ generally results in lower soil T and vice versa, which we also observed in our data. In the RRV, a higher soil θ in the soil early in the spring is often thought to delay or prevent spring planting from occurring, thus resulting in fewer growing days and subsequent crop yield losses leading to a reduction in profits for farmers (Seelan et al., 2003). Farmers have generally concluded that inceases in soil temperature near the soil surface in the early spring can help indicate tillage system effectiveness. Our results indicate these generalizations for soil warming and drying to be more complex. In this study, the soil warming and drying under varying reduced tillage practices appear to be more strongly affected by the external environment (rainfall), environmental losses (evaporation), soil texture, plant uptake, and/or a combination of these factors than that by tillage.

Soil T prior to spring tillage generally showed no significant differences among any tillage treatment at any soil depth. After spring tillage, few significant differences occurred for all farms and soil series. In our handheld measurements, instances where there was a greater mean soil T under CP for all soil depths when compared to other tillage treatments was consistent with when CP was also significantly lower in soil θ. This relationship was expected, but may be of concern later in the growing season as reduced soil θ can lead to issues with the plant's ability to take up water during periods of drought or reduced rainfall. Although CP tillage treatments generally displayed greater mean soil T in all farms, based on the handheld measurements, comparable soil warming was observed under STC and STS treatments. Based on our near continuous measurements of mean soil T, when CP, STC-IN, and STS-IN zones were significantly greater than other zones and treatments, mean soil T in the ST zones were in many cases numerically higher than CP. In the later growing season, greater soil θ generally observed among STC and STS treatments in the Barney and Mooreton farms, respectively, can buffer soil temperatures during periods of rapid plant growth. These findings were similar to other studies examining reduced tillage practices effects on soil θ (Verhulst et al., 2011; Doorenbos and Kassam, 1979). Similar to Alvarez and Steinbach (2009), when soils were wet early in the spring prior to tillage, fewer significant differences were observed among tillage treatments; whereas differences in response became more distinct as soil drying and warming occurred.

Soil θ differences were more evident among CP and VT tillage treatments at all farms. Mean soil T under CP appeared to respond more quickly to changes in soil θ. For example, the higher volumetric water content observed in the VT as compared to the CP treatments in early June at the Barney farm can be attributed to two consecutive events of rainfall which resulted in 12 mm of accumulation on May 30th and May 31st (NDAWN, 2017). The subsequent drop in volumetric water content for the CP treatment mid-June, based on handheld measurements, can be attributed to greater soil warming and evaporation due to reduced crop residue. The higher soil θ observed in the early growing season under STC-BT, STS-BT, and VT treatments were a result of the greater crop residue on the soil surface, which likely reduced evaporation in the spring (Hatfield et al., 2001; Drury et al., 1999; Rasmussen, 1999; Farahani et al., 1998).

In our study, mean soil θ were generally higher in the STC-BT zones and STC-IN zones when compared to STS-BT zones and STS-IN zones, respectively, based on handheld measurements. This finding was similar to Wolkowski (2000) where soil θ were determined to be greater when residue was managed in the spring as compared to the fall. In our study, the STS treatments occurred in the fall, whereas STC treatments occurred in the spring. However, under near continuous measurements, greater mean soil θ in the STC and STS tillage treatments responded differently where STC-BT and STC-IN zones were generally higher at the Barney farm, whereas STS-BT and STS-IN zones were generally higher at the Mooreton farm. This leads us to infer that soil texture (Barney, sandy loam and Mooreton, clay loam) could play a role in the effectiveness of the varying strip tillage implements in conserving soil volumetric water content in a frigid, wet soil.

An overall decrease in soil θ at each farm from early to mid-July, can be explained by rapid crop growth and crop water uptake. Observed variances in soil θ at all farms could be attributed to the different tillage system responses to crop water uptake (Wagger and Denton, 1992). Overall, soil θ under STC-IN and STS-IN zones showed the least variability over time during the growing season. During the two consecutive precipitation events observed at the Barney farm, although soil T in the STC-IN and STS-IN zones increased, the soil θ did not drop, but increased instead as a result of higher crop residue in the tilled zone improving moisture holding capacity by reflecting solar radiation. Near continuous measurements during the growing season at the Barney and Mooreton farms also demonstrated the effectiveness of strip-tillage implement in conserving soil θ. At the Mooreton farm, mean values under STC-IN were numerically less than other treatments, though not significantly different. At the Barney farm, mean values under STC-IN were generally higher than the other treatments, also not significantly different.

Generally, soil-surface crop residue reflects solar radiation and acts as an insulator to reduce soil surface T (Fabrizzi et al., 1995; Schinners et al., 1994; van Wijk et al., 1959). At all farms and observed transects, ST-IN demonstrated the ability to increase soil T comparatively to CP, while ST-BW demonstrated a greater ability to conserve a significantly greater amount of soil θ as compared to CP. This conservation of soil θ would be beneficial in the Upper Great Plains and particularly in the RRV during periods of low precipitation during the growing season (Morris et al., 2010). Vetsch and Randall (2002) examined ST, NT, and CP tillage treatments and determined that ST had a greater ability to conserve water when compared to the other treatments. The higher soil θ under ST treatments could result in more water availability for crop uptake, subsequent growth and crop yield. Other studies have examined reduced tillage practices in comparison with more aggressively tilled soils and demonstrated that reduced tillage treatments resulting in slightly lower soil T and increased soil θ could result in reduced crop growth in the early growing season (Opoku et al., 1997; Kaspar et al., 1990; Al-Darby and Lowery, 1987). However, we did not observe this for any of the farms and soil series during our study, as few significant differences in crop yields were observed among tillage practices at the three farms in our study.

Soil Chemical Properties

Soil samples were collected in June, during the rapid growth stages for both corn and soybean, when nutrients were being taken up by the plant's roots. When soil tillage affected soil chemical properties, the differences can likely be attributed to how and where fertilizers were placed among the tillage treatments (Duiker and Beegle, 2006; Rehm, 2005; Djodjic et al., 2002; Keller and Mengel, 1986; Miller and Ohlrogge, 1958). For instance, all differences tended to either 1) occur among the zones within or between the tilled strips of the STC and STS treatments (i.e., directly in or between where fertilizers were banded at the time of tillage) or 2) occur between tillage practices with surface broadcasted fertilizers (i.e., CP and VT) vs. tillage practices with banded fertilizers (i.e. STC and STS). No differences were observed between the two tillage practices with surface broadcasted fertilizers (i.e., CP and VT) for any chemical property in all transects at all farms. Similarly, other studies have also reported few, if any, differences in soil chemical properties due to tillage practices within the growing season. Licht and Al-Kaisi (2005b) reported plant uptake of nitrogen and soil N concentrations at the V6, V12, VT, and R6 corn growth stages under CP and ST practices. They observed no significant differences in plant uptake of N among tillage practices. However, soil N concentrations in their CP treatments were generally higher, but not always significant, than the other tillage practices.

In our study, similar results were observed with soil NO_3-N concentrations around the V6 to V8 growth stages being similar or significantly greater in the CP and VT as compared to STC and STS in all sample transects at the three farms.

During field observations in 2016 at the Mooreton farm, corn plants in all VT plots showed visible symptoms of plant N deficiency. Earlier that year, an unrelated issue prevented the farmer from having access to the VT implement and prevented a second VT pass to incorporate the broadcasted fertilizer into the VT plots. A significant portion of the unincorporated N fertilizer likely denitrified within the crop residue layer and was lost to the atmosphere. Therefore, we relate this to the cause of the observed plant N deficiency symptoms in the VT plots, although this effect was not detected in the soil chemical property analysis. No plant N deficiencies were observed for any plots in the other tillage practices at the Mooreton farm.

Soil Penetration Resistance

Monitoring soil resistance is important because of the inverse relationship it has with root penetration and elongation (Mirreh and Ketcheson, 1973). A higher observed penetration resistance in reduced tillage systems could indicate restricted root penetration and be demonstrated through subsequent losses in crop yields (Ketcheson, 1980), thus contributing to the hesitation from producers to implement such practices. Licht and Al-Kaisi (2005a) examined the relationship between penetration resistance and soil volumetric water content for CP, ST, and NT practices and determined that penetration resistance increased as the growing season progressed and where soil θ was depleted. Our results were contradictory as we observed penetration resistance to decrease as the growing season progressed. We attribute this variation in response to the smectite nature of our soils. Wetting and drying processes can reduce soil penetration resistance due to shrinking and swelling with results more pronounced in clayey soils (Jabro et al., 2013; Abou Najm et al., 2010). In our study, penetration resistance was similar among STC-IN, STS-IN, and CP tillage practices and closely related among STC-BT, STS-BT, and VT tillage practices. These relationships mirrored those observed when examining soil θ. Differences we observed in-row and between-the-row for both STC and STS practices is similar to findings by Raper et al. (1994) where a reduced penetration resistance was observed in-row as compared to between-the-row.

Plant Populations, Plant Heights, and Crop Yields

Plant populations and plant heights determined in June of each year can provide insights on crop germination success and timing among the tillage practices. However, no significant differences were observed in our study, suggesting that tillage did not have any practical effects on crop germination success and timing. Similar results were observed by Licht and Al-Kaisi (2005a, 2005b) where emergence of corn under CP and ST practices was examined, indicating no differences in the emergence rates. No significant differences in crop yields were observed for all farms under the soybean crop phase which is consistent with other studies (Daigh et al., 2017; Sindelar et al., 2015; Wilhelm and Wortmann, 2004; Brown et al, 1989). The generally lower corn yield in STS observed at the Fergus Falls farm in 2015 could be a result of soil smearing in the tilled strip during somewhat wet soil conditions in the fall. During fall tillage, the STS implements were delivered to the farm a few days later than when the CP and VT tillage was performed. Precipitation during these few days resulted in wetter soil conditions when the STS plots were tilled. These conditions resulted in a greater potential for soil smearing when using shanks in wet soil conditions. Clayey soils, with a higher soil θ level that are worked with a shank can result in a poor seedbed where the shank cuts a slit in the soil and poor seed-soil contact could result in lower plant populations and reduced crop yields (Evans et al., 2010). The generally lower corn yields in VT observed at the Mooreton farm in 2016 is likely the result of a second spring VT pass to incorporate N fertilizer not being possible due to equipment availability. Therefore, tillage systems appear to be more likely to induce crop yield differences if fertilizers are not sufficiently incorporated or lack sufficient incorporation with the soil rather than any differences in soil T and θ conditions. Borges and Mallarino (2001) examined fertilizer placement in corn fields under reduced tillage and determined deep-banding of nutrients reduced surface runoff and helped improve yield. Fernández and White (2012) examined NT and ST practices in a corn-soybean field under deep banded and broadcast fertilizer applications and determined that deep banding increased soil P and K values while also producing a greater number of corn kernels resulting in an increased crop yield.

Brown et al. (1989) examined the variations in corn and soybean responses to tillage and determined that a later planting date for soybean, when compared to corn, may lessen the effect of frigid early-season soil T. While this may be true, Vetsch et al. (2007) examined the yield response for corn-soybean rotational tillage under NT, CP, and spring field cultivator and concluded that there was no consistent relationship between soil θ , soil T, and yield among the various tillage practices during the corn crop phase. Our study identified no significant differences in plant population count or plant heights, thus indicating that plant emergence was likely not effected by tillage. Vetsch and Randall (2002) examined CP, zone-tillage, and ST practices in frigid corn-corn and corn-soybean rotated fields and determined that competitive yields could be produced under reduced tillage with added benefits for the soil from added residue coverage. In corn-soybean fields they also determined that yields were more significantly affected by starter fertilizer than by tillage system. We have similar findings that at the Barney farm under corn and soybean crop phases in 2015 and 2016, respectively, exhibited no significant differences in yields. We could attribute these similarities to the split nitrogen fertilizer application management practice that was implemented by the Barney farm producer.

Long-term corn and soybean responses to tillage practices have indicated very few significant differences in yield among varying reduced tillage systems (Daigh et al., 2017; Sindelar et al., 2015). A 16-year study in Nebraska examined CP, tandem disk, moldboard plow, NT, and ridge-tillage effect on corn dry matter and found only 6 years of measured differences of the 16 growing seasons in their study (Sindelar et al, 2015). Daigh et al. (2017) examined eight sites with long-term corn-soybean rotated fields under NT and CP for a duration of between 8 and 51 years. They reported only a few years of significant differences in crop yields. Our study is short (2 years) but ongoing to determine the long-term relationship between tillage practice and crop yields.

Implications and Recommendations for Producers

The choice of tillage practices a producer selects varies based upon multiple factors. Soil texture, crop type, climate, and socioeconomic effects (yields and profits) are among the varying reasons of selecting a conservation or reduced tillage practice for producers (Gajri et al., 2002; Vetsch and Randall, 2002). However, soil physical and chemical characteristics play a major role in determining which conservation tillage may be most suitable for an individual producer. A study conducted by Buman et al. (2004) examined the effects of reduced tillage practices in corn-soybean field on 13 field sites over five years using full-scale implements. General findings concluded no significant differences in soil quality and crop yield among the varying practices; however, crop profits were highest in ST and NT practices in four of the five years. These findings indicate that it is important for producers, crop consultants, researchers and others to consider not only crop yield as a measure of success in practice, but also overall profits when evaluating alternative practices.

Strip tillage treatment provides the benefits of soil warming and drying during early growing season with no significant effect on crop emergence. Strip tillage provides the benefits of reducing producers' time and expense with no significant differences on crop yields. Split applications of urea and ammonium nitrate (UAN) during crop growth with starter fertilizer at planting could increase crop yield due to improved nutrient uptake. Spring banding of fertilizer reduces nutrient losses due to environmental factors especially in flat, flood-prone areas with high clay content. Crop residue helps to reduce soil erosion, increases water infiltration, and builds soil health during drought months. If alternative reduced tillage practices result in similar yields and reduce time and expense (with fewer passes on the land), then producers in the region may consider changing their tillage practices to conserve soil health for long-term added benefits.

Conclusions

Our two-year study indicates that in a frigid environment, reduced tillage practices (CP, STC, STS and VT) can result in significant differences among soil T, soil θ, soil penetration resistance, soil chemical properties, and crop residue. Overall CP, STC-IN, and STS-IN were generally similar and significantly different from VT, STC-BT, and STS-BT when examining soil T, soil θ, and soil penetration resistance. Despite any significant differences observed, statistically there were few differences in crop yield as affected by reduced tillage systems. Statistical differences observed in soil T, soil θ, and soil penetration resistance were inconsistent with yield. Instead, fertilizer application (split method vs. starter), timing (fall vs. spring), and method (banded vs. broadcasting) were consistent with significant differences of crop yields both in this study and in other studies reported in the literature. Therefore, we conclude that most, if any, perceived or real differences in soil warming and drying among CP, STC, STS, and VT tillage practices do not often result in crop yield gains or losses in the frigid corn-soybean fields of the RRV and surrounding areas.

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GENERAL CONCLUSIONS

The effect of reduced tillage treatments on soil physical and chemical parameters were not isolated to a single reduced tillage practice which outperformed all others. Soil temperatures in chisel plow (CP), strip tillage with coulter in the tilled berm (STC-IN), and strip tillage with shank in the tilled berm (STS-IN) were typically higher at multiples depths than vertical tillage (VT), strip tillage with coulter between the tilled berm (STC-BT), and strip tillage with shank between the tilled berm (STS-BT), which did not differ among each other. These relationships were consistent throughout many of the parameters we examined. For example, CP, STC-IN, and STS-IN generally displayed lower soil volumetric water contents and a lower soil penetration resistance when compared with VT, STC-BT, and STS-BT. At all farms, ST in-row zones demonstrated the ability to increase soil temperatures while ST between-the-row zones demonstrated great ability to conserve a greater amount of soil volumetric water contents. The use of ST indicated added benefits for the Upper Great Plains where precipitation during the growing season can be low and a short growing season requires timely soil warming. Overall, crop yields in our study were not significantly affected by a single reduced tillage treatment. Differences that occurred are could be a result of nutrient management practices which differed across farms and reduced tillage treatments. Based on the literature reviewed, more research is needed to determine the long-term effects of these reduced tillage treatments. Likewise, further research is needed to determine the most effective nutrient management practices for reduced tillage practices in frigid soils with a short growing season. Evidence from our research on soil warming and drying and the consequences on crop yield should more accurately inform researchers, consultants, and land managers of the true relationships that exist between reduced tillage practice implementation and soil physical and chemical parameters in our region.

APPENDIX. ADDITIONAL TABLES

Table A1. Analysis of variance P-value table for mean soil volumetric water content (θ) and soil temperature (T) analyzed for fixed effects of Date, Tillage, Depth, and their interactions in the Wyndmere and Delamere soil series sampling transect at the Barney farm, in the Barnes and Lakepark soil series sampling transect at the Fergus Falls farm, and in the Fargo NE soil series sampling transect at the Mooreton farm. Daily means were calculated from handheld measurements collected in 7 date measurements in 2015 and 12 date measurements in 2016. Data were collected from March 2015 through August 2016.

Farm	Soil Transect	Source	T	θ
Barney	Wyndmere	Date	<0.0001	<0.0001
		Tillage	<0.0001	<0.0001
		Depth	<0.0001	
		Tillage*Depth	<0.0001	
		Date*Tillage	<0.0001	<0.0001
		Date*Depth	<0.0001	
		Date*Tillage*Depth	<0.0001	
	Delamere	Date	<0.0001	<0.0001
		Tillage	<0.0001	<0.0001
		Depth	<0.0001	
		Tillage*Depth	<0.0001	
		Date*Tillage	<0.0001	<0.0001
		Date*Depth	<0.0001	
		Date*Tillage*Depth	<0.0001	
Fergus Falls	Barnes	Date	<0.0001	<0.0001
		Tillage	<0.0001	<0.0001
		Depth	<0.0001	
		Tillage*Depth	<0.0001	
		Date*Tillage	<0.0001	<0.0001
		Date*Depth	<0.0001	
		Date*Tillage*Depth	<0.0001	
	Lakepark	Date	<0.0001	<0.0001
		Tillage	<0.0001	<0.0001
		Depth	<0.0001	
		Tillage*Depth	<0.0001	
		Date*Tillage	<0.0001	<0.0001
		Date*Depth	<0.0001	
		Date*Tillage*Depth	<0.0001	
Mooreton[†]	Fargo	Date	<0.0001	<0.0001
		Tillage	<0.0001	<0.0001
		Depth	<0.0001	
		Tillage*Depth	<0.0001	
		Date*Tillage	<0.0001	<0.0001
		Date*Depth	<0.0001	
		Date*Tillage*Depth	<0.0001	

[†]Values at the Mooreton farm are for 2016 only and in the subsurface drained, non-saline soil (i.e. NE quadrant).

Table A2. Analysis of variance P-value table for mean daily soil volumetric water content (θ) and soil temperature (T) parameters (i.e., mean, max, and min) analyzed for fixed effects of date, tillage, depth, and their interactions in the Fargo soil series sampling transect at the Mooreton farm. Daily means were calculated from near-continuous measurements collected at 30 minute intervals each day. Data was collected for 173 days from May 2016 through October 2016. Vertical tillage was not included in the analysis due to only one experimental block with a functional datalogger.

Source	Month-Year	θ (m^3 m^{-3})	T mean	T max	T min
Day	May - 2016	0.03	<0.0001	<0.0001	<0.0001
	June - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	July - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Aug - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Sept - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Oct - 2016	<0.0001	<0.0001	<0.0001	<0.0001
Tillage	May - 2016	0.53	0.66	0.23	0.53
	June - 2016	0.43	0.83	0.06	0.62
	July - 2016	0.24	0.39	0.07	0.67
	Aug - 2016	0.35	0.12	0.10	0.62
	Sept - 2016	0.55	0.09	0.26	0.51
	Oct - 2016	0.64	0.79	0.60	0.40
Depth	May - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	June - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	July - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Aug - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Sept - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Oct - 2016	<0.0001	<0.0001	<0.0001	<0.0001
Tillage*Depth	May - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	June - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	July - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Aug - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Sept - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Oct - 2016	<0.0001	<0.0001	<0.0001	<0.0001
Day*Tillage	May - 2016	1.00	1.00	0.48	1.00
	June - 2016	1.00	0.80	0.50	1.00
	July - 2016	1.00	0.53	<0.01	0.67
	Aug - 2016	0.94	0.98	<0.0001	1.00
	Sept - 2016	0.87	0.02	0.12	1.00
	Oct - 2016	1.00	<0.0001	0.01	0.01
Day*Depth	May - 2016	1.00	<0.0001	<0.0001	<0.0001
	June - 2016	0.99	<0.0001	<0.0001	<0.0001
	July - 2016	1.00	<0.0001	<0.0001	<0.0001
	Aug - 2016	1.00	<0.0001	<0.0001	<0.0001
	Sept - 2016	1.00	<0.0001	<0.0001	<0.0001
	Oct - 2016	<0.0001	<0.0001	<0.0001	<0.0001
Day*Tillage*Depth	May - 2016	1.00	1.00	1.00	1.00
	June - 2016	1.00	1.00	1.00	1.00
	July - 2016	1.00	1.00	1.00	1.00
	Aug - 2016	1.00	1.00	1.00	1.00
	Sept - 2016	1.00	1.00	1.00	1.00
	Oct - 2016	1.00	<0.0001	0.94	0.85

Table A3. Analysis of variance P-value table for mean daily soil volumetric water content (θ) and soil temperature (T) parameters (i.e., mean, max, and min) analyzed for fixed effects of date, tillage, depth, and their interactions in the Wyndmere soil series sampling transect at the Barney farm. Daily means were calculated from near-continuous measurements collected at 30 minute intervals each day. Data was collected for 311 days from November 2015 through October 2016. Data shown here are for the fall and winter months.

Source	Month-Year	θ (m^3 m^{-3})	T mean	T max	T min
Day	Nov-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Dec-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Jan-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Feb-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Mar-2016	<0.0001	<0.0001	<0.0001	<0.0001
Tillage	Nov-2015	0.88	0.52	0.22	0.66
	Dec-2015	0.80	0.88	0.89	0.85
	Jan-2016	<0.001	0.06	0.06	0.06
	Feb-2016	<0.001	0.23	0.28	0.18
	Mar-2016	0.45	0.88	0.87	0.87
Depth	Nov-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Dec-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Jan-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Feb-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Mar-2016	<0.0001	<0.0001	<0.0001	<0.0001
Tillage*Depth	Nov-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Dec-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Jan-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Feb-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Mar-2016	<0.0001	<0.0001	<0.0001	<0.0001
Day*Tillage	Nov-2015	1.00	1.00	1.00	1.00
	Dec-2015	1.00	0.17	0.38	0.07
	Jan-2016	1.00	<0.0001	<0.0001	<0.0001
	Feb-2016	0.86	<0.0001	<0.0001	<0.0001
	Mar-2016	0.99	1.00	1.00	0.98
Day*Depth	Nov-2015	<0.0001	<0.0001	<0.0001	<0.0001
	Dec-2015	<0.0001	0.46	0.40	0.12
	Jan-2016	<0.0001	<0.0001	<0.0001	<0.0001
	Feb-2016	0.07	<0.0001	<0.0001	<0.0001
	Mar-2016	<0.0001	<0.0001	<0.0001	<0.0001
Day*Tillage*Depth	Nov-2015	1.00	1.00	1.00	1.00
	Dec-2015	1.00	1.00	1.00	1.00
	Jan-2016	1.00	1.00	0.98	1.00
	Feb-2016	1.00	0.98	0.98	0.94
	Mar-2016	1.00	1.00	1.00	1.00

Table A4. Analysis of variance P-value table for mean daily soil volumetric water content (θ) and soil temperature (T) parameters (i.e., mean, max, min, and amplitude) analyzed for fixed effects of date, tillage, depth, and their interactions in the Wyndmere soil series sampling transect at the Barney farm. Daily means were calculated from near-continuous measurements collected at 30 minute intervals each day. Data was collected for 311 days from November 2015 through October 2016. Data shown here are for the spring and summer months.

Source	Month-Year	θ (m^3 m^{-3})	T mean	T max	T min
Day	April - 2015	<0.0001	<0.0001	<0.0001	<0.0001
	May - 2015	0.60	<0.0001	<0.0001	<0.0001
	June - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	July - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Aug - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Sept - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Oct -2016	<0.001	<0.0001	<0.0001	<0.0001
Tillage	April - 2015	0.82	0.99	0.92	0.91
	May - 2015	0.57	0.13	0.20	0.31
	June - 2016	0.59	0.15	0.11	0.45
	July - 2016	0.65	0.88	0.72	0.60
	Aug - 2016	0.77	0.88	0.96	0.59
	Sept - 2016	0.53	0.64	0.84	0.25
	Oct -2016	0.49	0.15	0.05	0.14
Depth	April - 2015	<0.0001	<0.0001	<0.0001	<0.0001
	May - 2015	<0.0001	<0.0001	<0.0001	<0.0001
	June - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	July - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Aug - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Sept - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Oct -2016	<0.0001	<0.0001	<0.0001	<0.0001
Tillage*Depth	April - 2015	<0.0001	<0.0001	<0.0001	<0.0001
	May - 2015	<0.0001	<0.0001	<0.0001	<0.0001
	June - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	July - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Aug - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Sept - 2016	<0.0001	<0.0001	<0.0001	<0.0001
	Oct -2016	<0.0001	<0.0001	<0.0001	<0.0001
Day*Tillage	April - 2015	1.00	1.00	1.00	1.00
	May - 2015	1.00	1.00	1.00	0.94
	June - 2016	1.00	1.00	1.00	0.08
	July - 2016	0.98	0.15	0.02	0.91
	Aug - 2016	1.00	1.00	1.00	0.84
	Sept - 2016	1.00	0.78	<0.01	0.34
	Oct -2016	1.00	0.12	<0.0001	0.78
Day*Depth	April - 2015	1.00	<0.0001	<0.0001	<0.0001
	May - 2015	1.00	<0.0001	<0.0001	<0.0001
	June - 2016	1.00	<0.0001	<0.0001	<0.0001
	July - 2016	<0.001	<0.0001	<0.0001	<0.0001
	Aug - 2016	0.37	<0.0001	<0.0001	<0.0001
	Sept - 2016	0.12	<0.0001	<0.0001	<0.0001
	Oct -2016	1.00	<0.0001	<0.0001	<0.0001
Day*Tillage*Depth	April - 2015	1.00	0.90	1.00	1.00
	May - 2015	1.00	1.00	1.00	1.00
	June - 2016	1.00	1.00	1.00	1.00
	July - 2016	1.00	1.00	1.00	1.00
	Aug - 2016	1.00	1.00	1.00	1.00
	Sept - 2016	1.00	0.98	0.99	1.00
	Oct -2016	1.00	0.97	0.17	1.00

Table A5. Summary of the maximum mean soil temperature for near continuous measurements for soil series and depths that were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT) and depth interactions] at the Barney and Mooreton farms for data collected from 2016.

Farm	Time	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	--------------------------------	-------	-------°C-------	-------	-------	--------------------------------
Barney	Nov 2015	5	12.6ab†	13.2a	12.6ab	12.6ab	12.6ab	12.3b
		10	12.9ab	13.3a	12.9ab	12.7ab	12.5b	12.7ab
		40	14.7a	13.5b	14.1ab	14.2ab	14.2ab	14.5a
	Dec 2015	5	10.1b	10.9a	10.4ab	10.4ab	10.3ab	10.1b
		10	10.5ab	11.0a	10.5ab	10.5ab	10.2b	10.5ab
		40	11.9a	11.1b	11.7ab	11.8a	11.7ab	11.9a
	Jan 2016	5	7.6b	9.3a	9.9a	9.9a	9.3a	8.6ab
		10	8.1b	9.4ab	9.9a	10.0a	9.1ab	9.2ab
	May 2016	5	31.3a	28.1b	30.8a	31.2a	32.1a	31.4a
	June 2016	5	35.6a	32.1b	35.0a	36.3a	36.8a	35.4a
		40	30.2ab	31.7ab	30.7ab	29.9b	31.8a	29.9b
	July 2016	5	34.2ab	32.4b	34.5ab	36.7a	35.1ab	33.5ab
	Sept 2016	5	28.0ab	27.3b	27.8ab	28.6a	28.1a	27.9ab
	Oct 2016	5	22.8b	22.9b	22.5b	25.8a	23b	22.7b
		10	22.8ab	23.1ab	22.4b	23.9a	22.6b	22.5b
Mooreton	May 2016	5	30.1a	NA‡	29.6a	29.5a	28.9b	28.6b
	June 2016	5	35.9a	NA	35.3a	35.2a	34.3b	34.4b
		10	36.2a	NA	35.9a	35.6ab	35.4ab	35.0b
	July 2016	5	37.3a	NA	36.2ab	36.3ab	35.4b	35.5b
		10	37.6a	NA	36.8ab	36.6ab	36.3b	35.9b
	Aug 2016	5	35.7a	NA	34.5ab	34.7ab	33.8b	34.1b
		10	36.1a	NA	35.1ab	35.1ab	34.7ab	34.5b
	Sept 2016	5	31.0a	NA	30.2ab	30.4ab	29.5b	29.8ab

†Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

‡ NA-Not Available due to dysfunctional datalogger

Table A6. Summary of the minimum mean soil temperature for near continuous measurements for soil series and depths that were significantly affected by reduced tillage practices [chisel plow (CP), vertical tillage (VT), strip tillage with coulter in the tilled berm (STC-IN), strip tillage with coulter between the tilled berm (STC-BT), strip tillage with shank in the tilled berm (STS-IN), and strip tillage with shank between the tilled berm (STS-BT) and depth interactions] at the Barney and Mooreton farms for data collected from Nov. 2015 to Oct. 2016.

Farm	Time	Depth	CP	VT	STC-IN	STC-BT	STS-IN	STS-BT
		cm	-----------	-----------	-----------	°C	-----------	-----------
Barney	Nov 2015	5	10.6ab†	12a	10.2ab	9.9b	10.5ab	10.4ab
		40	14.2a	11.8b	13.6ab	13.7ab	13.7ab	14a
	Dec 2015	5	9.5b	10.7a	10.2ab	10.2ab	9.9ab	9.8b
		10	10.2ab	10.9a	10.3ab	10.3ab	9.9b	10.3ab
		40	11.9a	10.8b	11.7ab	11.8a	11.6ab	11.9a
	Jan 2016	5	6.1b	8.8a	9.5a	9.6a	8.6a	7.6ab
		10	7.0b	8.9ab	9.7a	9.7a	8.6ab	8.6ab
	Feb 2016	5	7.2b	8.9ab	9.6a	9.6a	9.2ab	8.4ab
	April 2016	5	13.8ab	14.4a	13.5ab	13.4b	13.8ab	14.4a
		10	14.5ab	14.9a	14.0ab	13.9b	14.0ab	14.2ab
	June 2016	40	15.2ab	14.3b	15.4a	15.6a	15.5a	15.5a
	May 2016	5	25.5a	25.1ab	25.2ab	23.9b	25.4a	25.3a
	June 2016	5	29.5a	29.2ab	25.2ab	27.9b	29.1ab	29.1ab
	Sept 2016	5	25.2a	25.7a	25.2a	24.4b	25.2a	25.1a
	Oct 2016	5	19.4a	20.0a	19.6a	16.1b	19.7a	19.0b
Mooreton	Oct 2016	5	17.0b	NA‡	17.9ab	17.7ab	17.7ab	18.0a

†Different letters within a row are significantly different at the 0.05 level using Tukey's HSD test.

‡ NA-Not Available due to dysfunctional datalogger